A Comprehensive Review on Fuel Cell UAV Key Technologies: Propulsion System, Management Strategy, and Design Procedure

Liangcai Xu, *Member, IEEE*, Yigeng Huangfu, *Senior Member, IEEE*, Rui Ma, *Senior Member, IEEE*, Renyou Xie, *Member, IEEE*, Ziyou Song, *Member, IEEE*, Dongdong Zhao, *Member, IEEE*, Yongheng Yang, *Senior Member, IEEE*, Yupeng Wang, *Senior Member, IEEE*, and Liangfei Xu

***Abstract*— Unmanned aerial vehicles (UAVs) can be regarded as one of the most emerging technologies. Compared with piloted aerial vehicles, UAVs qualify for higher safety and lower cost, and they are more suitable for dangerous missions. Recently, fuel cell (FC) UAVs have obtained more and more attention due to their relatively higher energy density. However, their propulsion system still needs to be further improved to meet different requirements of performing difficult tasks. This article aims to give a comprehensive review of the key technologies of FC UAVs. First, various architectures of the propulsion system and corresponding advantages and disadvantages are introduced. Then, three kinds of management strategies for FC UAVs are reviewed. Next, some special applications and considered design procedures are summarized. Compared with other review articles, this article tries to cover more aspects of FC UAVs. Since these aspects have a tight relationship with each other, giving a comprehensive review can be more beneficial to us to understand the state-of-the-art development of propulsion systems for FC UAVs. The conclusions show that advanced propulsion architectures, efficient online energy management strategies, and professional design procedures are still in urgent demand in the commercial process of FC UAVs.**

***Index Terms*— Aviation, design procedure, energy management strategies (EMSs), fuel cell (FC), propulsion architectures, unmanned aerial vehicle (UAV).**

I. INTRODUCTION

UNMANNED aerial vehicles (UAVs) can be considered flying robots, which have received much research efforts from scientists in the past few decades [1]. The main reason is that UAVs can be used for dangerous and difficult missions [2], which will significantly guarantee the worker's safety and health. Moreover, it is also convenient for humans to execute remote operations by UAVs [3]. Therefore, the efficiency of the whole human society is greatly improved. Meanwhile, due to the development of advanced manufacturers and advances in material science, various types of UAVs can be found on the market. For example, UAVs can be classified as fixed wing, rotary wing, and flapping wings when their shapes are considered [4]. Furthermore, regarding the power supply sources, there are solar-powered, battery-powered, fuel cell (FC)-powered, and internal combustion engine (ICE)-powered UAVs. Moreover, respecting size, they can be categorized as nano, micro, mini, medium, and large UAVs [5]. All these UAVs could be applied in various tasks, such as traffic monitoring, infrastructure inspection, monitoring, environmental monitoring, delivery service, agriculture preservation, wireless coverage, and even military applications [6]. According to the market research report released in 2019, the global commercial UAV market size would reach U.S. $17 billion in 2024 [7]. Because of these tremendous benefits, more and more companies and multinationals are putting a lot of effort into the improvement of UAVs.

As one of the most crucial parts, the innovations in propulsion systems have been the primary driver of the progress in UAVs. In the last few decades, the ICE always dominated as the main power source due to its high power and energy density [8]. However, the ICE-based UAVs also have many disadvantages, such as high noise, high cost, high vibration, and especially pollutants emissions (i.e., greenhouse gases, NO_x and SO_2). To reduce their impacts on the environment, hybrid architecture for the propulsion system has been proposed and researched deeply, which contains an ICE source and battery source [9]. To some extent, this method is effective. However, when considering the shortage of traditional foil fuel sources and serious environmental pollution, this hybrid method is not appropriate. Moreover, the investment in the international policy to phase out ICE-based vehicles has already shown that the electrification of aviation is a big trend [10].

Until now, there are many kinds of electric power sources, such as fuel cells, solar panels, batteries, and supercapacitors [11]. Among them, the battery can be said to be the most widely used electric power source. How-

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Liangcai Xu is with the School of Automation, Northwestern Polytechnical University, Xi'an 710072, China, and also with the Department of Mechanical Engineering, National University of Singapore, Singapore 117575.

Yigeng Huangfu, Rui Ma, Renyou Xie, and Dongdong Zhao are with the School of Automation, Northwestern Polytechnical University, Xi'an 710072, China (e-mail: rui.ma@nwpu.edu.cn).

Ziyou Song is with the Department of Mechanical Engineering, National University of Singapore, Singapore 117575.

Yongheng Yang is with the College of Electrical Engineering, Zhejiang University, Hangzhou 310027, China.

Yupeng Wang is with the Powertrain Department, General Research and Design Institute, FAW, Changchun 130011, China.

Liangfei Xu is with the State Key Laboratory of Automotive Safety and Energy, Tsinghua University, Beijing 100084, China.

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ever, it has relatively low energy density and long charger time, which leads to UAV's poor endurance and low efficient flight time [12]. Up to date, the endurance of battery-powered UAVs has already reached 90 min due to the development of lithium-polymer batteries [13]. If a longer endurance time is required, the quantity of batteries needs to be increased. Sometimes, this solution is not practical because of the constraints of weight and space for the UAVs. Therefore, an alternative method should be proposed. This method should not only supply additional energy but also satisfy the limited conditions. Solar panels and fuel cells are two preferred candidates. Solar panels have already been widely applied to fixed-wing UAVs. In this way, solar energy could be converted to batteries during the daytime. Meanwhile, those solar panels almost do not affect the whole aircraft (i.e., space, weight, and aerodynamic structure) because they can be tightly attached to wings. However, solar panels are only convenient for fixed-wing aircraft and their performance could be significantly affected by the weather. What is more, additional large batteries must be used to keep the UAVs frying during the night. By contrast, fuel cells can not only be applied to any type of UAV but also can work continuously day and night. Besides, due to its propriety of high specific energy density, the endurance of fuel cell-powered UAVs is relatively longer than the pure battery-powered ones.

It should be noted that fuel cell-powered UAVs have been researched and developed since 1959 [14]. Up to now, although the performance of fuel cell UAVs has been significantly improved due to the contributions from a large number of researchers, there is still a long way to go before commercialization. Many technologies related to the fuel cell electric propulsion system need to be further improved to improve the durability, reliability, and fuel efficiency of fuel cell UAVs. Generally speaking, these key technologies mainly include propulsion system architecture, energy management strategies (EMSs), and design procedures for general fuel cell UAVs. For each key technology, there are several different selections or solutions. Therefore, to help engineers design fuel cell UAVs that could meet commercial needs, a comprehensive summary of these related technologies should be made. In this way, the potential challenges and prospects of these technologies can be summarized easily, which is very beneficial to the development of fuel cell UAVs. Recently, much review literature has been found to address different aspects of fuel cell-related technologies, for example, the strategies of the propulsion system on UAVs [15]; the fundamentals and applications of fuel cell technology [16]; evaluations of fuel cell stacks to achieve high altitudes in light aircraft [17]; the conclusions on barriers of scaling-up fuel cells [18]; proton exchange membrane fuel cell (PEMFC) system control methods [19]; life cycle evaluation of hydrogen and other potential fuels for aircraft [20]; future aircraft design concepts for energy efficiency and environmental protection [21]; fuel cell APU systems for aircraft [22]; and power supply and energy management for aerial vehicles [23]. These articles mainly focus on one aspect, and most of them fail to analyze the current state of technology development from the perspective of fuel cell UAV demand. Therefore, this article will first try to give a relatively comprehensive review of some key technologies of the whole propulsion system for fuel cell UAVs. From the authors' point, since all the technologies of propulsion systems have a tight relationship with each other, a comprehensive review will be more helpful to readers to understand them and be beneficial to the future development of fuel cell UAVs.

The rest of this review article will be organized as follows. Section II presents the different architectures of electric propulsion systems for these UAVs. The EMSs for fuel cell UAVs are given in Section III. Some special applications and corresponding design methods for different fuel cell UAVs can be found in Section IV. Finally, some conclusions will be made in Section V.

II. ELECTRIC PROPULSION ARCHITECTURES FOR FUEL CELL UAVS

The architecture and operation of the electric propulsion system are one of the most important key technologies for fuel cell UAVs. The better system architecture will bring better performance, such as longer endurance time and higher efficiency. Therefore, the objective of this section will focus on sorting out the three most popular electric propulsion system architectures and summarizing their respective advantages and disadvantages. For convenience, only the fuel cell stack and battery are selected as the power sources for the analysis of the propulsion system.

A. Pure Fuel Cell Power System

Due to the various advantages of the fuel cell system, Bradley *et al.* [24] developed a pure fuel cell-powered UAV in 2007. The detailed fuel cell power plant diagram and the system specifications are shown in Fig. 1. This propulsion system contains many important components, such as variable cathode flow control, liquid cooling, self-humidification, and variable cycle anode purging. To evaluate the overall performance of the pure fuel cell-powered UAV, a comprehensive test flight was carried out. The flight test process includes idle speed, high power, and nominal cruise. Also, Figs. 2–5 show the propulsion system losses in detail under these three conditions.

Under idle conditions, as shown in Fig. 2, when the 1.26 standard L/min hydrogen is supplied, a lower heating value (LHV) of 227 W can be obtained. However, almost 74% of the energy is wasted due to the higher frequency anode purging, and the net electricity generated by the fuel cell system is almost zero. Therefore, the overall efficiency of this power system is unsatisfactory. When the UAV started to take off or climb, it could be seen from Fig. 3 that the hydrogen utilization rate of the fuel cell propulsion system is above 88%. The efficiency of the motor controller and the propeller is 74% and 70%, respectively. Also, the efficiency of the whole propulsion system is 14%. As for the cruise condition, shown in Fig. 4, the UAV always maintains an altitude of 10 m and maintains a stable airspeed of 13.6 m/s. Similarly, the efficiency of the motor controller and the propeller is 66%

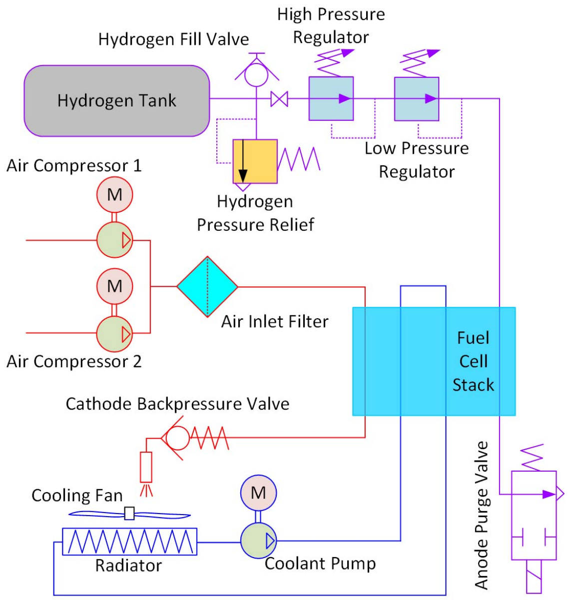


Fig. 1. Detailed power plant diagram of the pure fuel cell-powered UAVs [24].

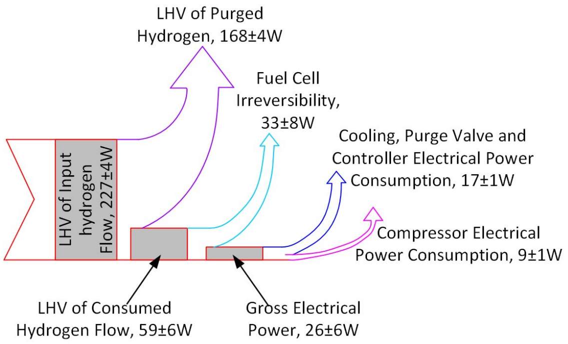


Fig. 2. Propulsion system losses under the idle condition [24].

and 80%, respectively. The overall propulsion efficiency from the hydrogen input to the propulsion system is about 18%.

The abovementioned research conducted by Bradley *et al.* [24] has validated that the concept of fuel cell aircraft is feasible. Besides, its operation complexity and system weight are also satisfactory. However, low efficiency, poor dynamic performance, and limited fault-tolerant capability hinder the development of UAVs powered by pure fuel cell systems. To make the pure fuel cell system more feasible for fuel cell UAVs, a lot of efforts have been put in by other researchers, for example, advanced hydrogen storage method [25], alternative onboard hydrogen generator method [26], high power density fuel cell stacks that are equipped with metal bipolar plates [27], high-efficiency power plant architecture [28], and a more compact balance of plant (BoP) [29]. In addition, series hybrid and parallel hybrid propulsion architectures are also common solutions to improve the performance of fuel cell propulsion systems.

B. Series Hybrid Power System

According to the published papers, patents, and other related documents, two main series-type electric propulsion system architectures can be summarized. One of them uses fuel cells and batteries as power components, and the fuel cells are used as the main power source. The other is to combine the fuel cell and the ICE to provide power for the UAVs, with the ICE as the main power source. The characteristics and working principles of these two systems are discussed in the following.

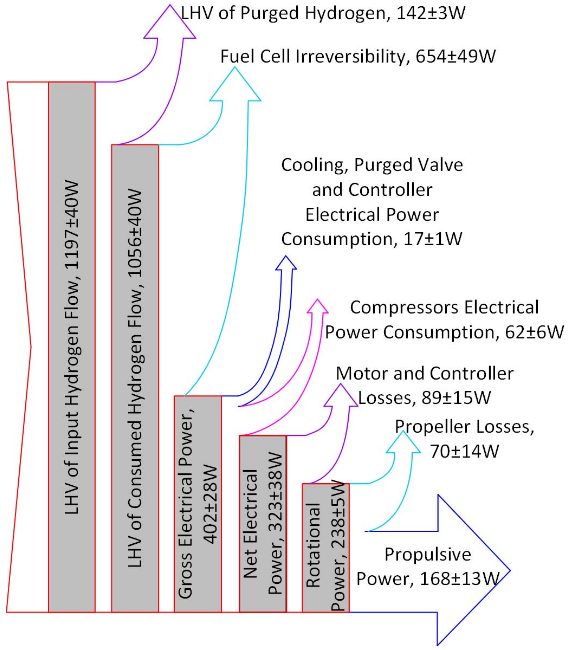


Fig. 3. Propulsion system losses under high-power conditions [24].

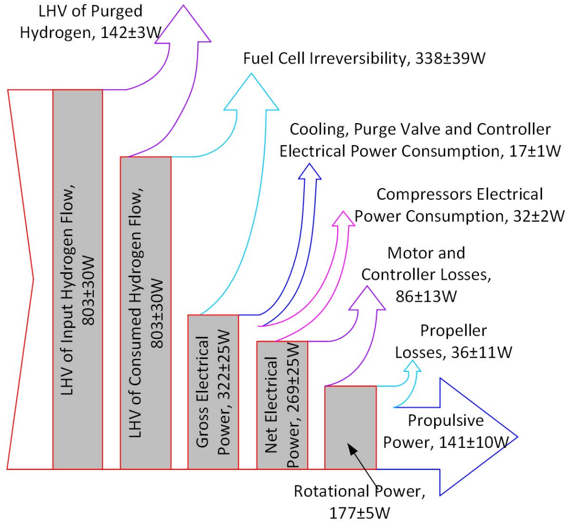


Fig. 4. Propulsion system losses under cruise conditions [24].

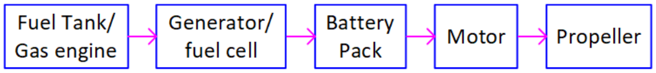


Fig. 5. Fuel cell and battery series hybrid electric propulsion configuration.

Fig. 5 shows a configuration diagram of a series of hybrid propulsion systems with fuel cells and battery packs [30]. In fuel cell-powered UAVs, the fuel tanks, engines, and generators can be replaced by fuel cell systems. Also, the fuel cell in the series configuration acts as an auxiliary power source to

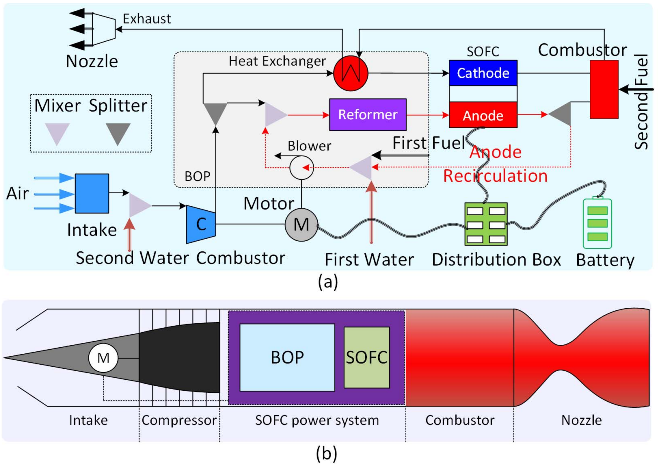


Fig. 6. Fuel cell and ICE series hybrid electric propulsion configuration. (a) Scheme diagrams of the turbine-less jet engine integrated with a fuel cell and steam injection. (b) Possible actual configuration of the engine [35].

charge the battery. Generally, in a series configuration system, the battery needs a larger size to meet the peak power demand. In contrast, since the fuel cell is only responsible for charging the battery, a smaller size can be selected. Moreover, the fuel cell stack can always work at the best efficiency and only start working when the battery's state of charge (SOC) reaches the predetermined threshold. Compared with a pure fuel cell power system, a hybrid power system in which a fuel cell and a battery are connected in series can avoid the waste of hydrogen, and the system's efficiency is also improved when the fuel cell UAV is working in an idle state [31]. Some tests are carried out in [99] and the results show that the extra weight for the series configuration is primarily due to the required generator and larger electric motor. Its operation complex is simple because the pure fuel cell system and the dynamic performance, and fault-tolerant capability are also greatly improved. Moreover, since the UAV propulsion motors usually require higher speeds, series hybrid systems are not quite suitable [34] and the fuel cell and battery series hybrid electric propulsion configuration may be more suitable for low-speed, high-torque applications, such as buses [32] and aircraft tractors [33].

Fig. 6 shows a schematic of an ICE (turbine-less jet engine) integrated with fuel cell and steam injection [35]. From Fig. 6(b), we can see that the solid oxide fuel cell (SOFC) is connected in series with the turbine-less jet engines. This architecture is defined as a hybrid system in which an ICE and a fuel cell are connected in series. The detailed operation steps will be described as follows. First, the atmosphere is compressed together with the intake air. The steam injection and evaporative cooling occur in the intake pipe. Then, a compressor is used to compress the steam, which is usually driven by an electric machine. The compressed flow is divided into two parts: one part is supplied to the reformer and the other part is supplied to the fuel cell cathode channel. Third, anode exhaust gas, fuel, and water are mixed and compressed by the blower to provide effective pressure for anode recirculation. The reformer is supplied with compressed fuel, water, and air, which means that the reforming reaction process will proceed successfully. The reformed products containing H_2, CO, CH_4, CO_2, and N_2 flow into the anode channel of the fuel cell, and then, electrochemical reactions occur in the fuel cell in sequence. Fourth, part of the exhaust gas from the anode channel of the fuel cell is recycled to the reformer, and the rest flows into the combustor. In addition, some fuel is also injected into the combustor to reach higher temperatures. Finally, the combustion chamber exhaust gas is supplied to the heat exchanger to heat the air entering the cathode channel of the fuel cell. After that, the exhaust gas expands and outputs propulsive force together with the nozzle. To further improve the efficiency of the entire system, Aguiar *et al.* [36] conducted a comprehensive study. A combined SOFC/gas turbine system running on liquefied hydrogen is considered. The corresponding results show that, compared with the single-cell stack design, when the fuel cell stack is modularized into multiple discrete stacks, the fuel is distributed in parallel, and the air is supplied in series, the system efficiency and system weight can be substantially improved. Adopting this technology, the UAV with a liquefied hydrogen payload of approximately 780 kg can achieve a one-week mission. The relevant system architecture and the corresponding layout diagram are shown in Fig. 7. However, the operation of this architecture is quite complex and the onboard liquefied hydrogen storage is not practically feasible.

In summary, due to fuel recovery and heat reuse, the efficiency of the IEC and fuel cell series hybrid system is relatively higher than that of the traditional pure fuel cell propulsion system. In addition, the thermal efficiency, specific thrust, and impulse of the hybrid power system also have obvious advantages over traditional turbojet engines [37], [38]. However, due to the existence of IEC engines, greenhouse gases and other harmful gases will still be produced.

C. Parallel Hybrid Power System

The parallel hybrid propulsion system is the most used and researched configuration in fuel cell UAVs. Generally, a parallel hybrid propulsion system can be divided into two configurations: active configuration with controlled dc–dc converters, and passive configuration, which is directly connected to the dc bus among all the power sources.

Fig. 8 shows the three main types of passive structures [39]. Although they seem to be slightly different, the principles of operation are quite different. For Fig. 8(a), the batteries are used as the main power source, which is similar to Fig. 4. The fuel cell system operates as a "range extender" system. When the SOC of batteries reaches a predetermined minimum value, the switch will be turned on and the fuel cell system will start generating electricity. Part of the electricity generated by the fuel cell system is provided to the motor, and the rest is used to charge the lithium-ion battery. This process continues until the SOC of the batteries reaches its predetermined maximum value. Since lithium-ion batteries play an important role in this structure, their selection and design are very important to the performance of the entire system. Generally, to meet the high-power demand caused by the large load disturbance,

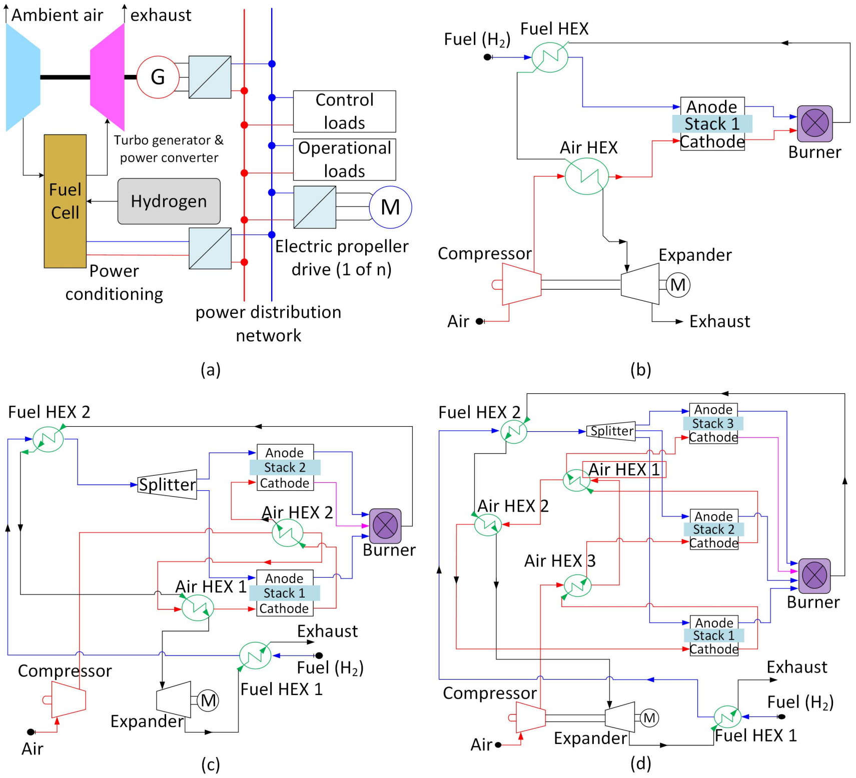


Fig. 7. Different stacks of SOFC combined with GT. (a) UAV power system architecture. (b) One-stack SOFC/GT system arrangement diagram. (c) Two-stack system arrangement diagram. (d) Three-stack system arrangement diagram [36].

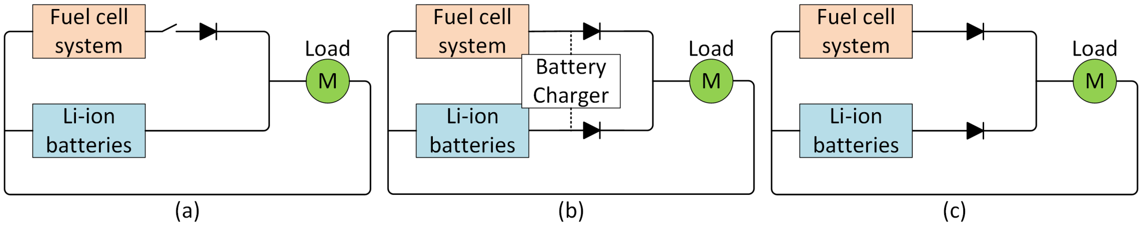


Fig. 8. Passive hybrid fuel cell/batteries power system configuration [39]. (a) First type with one diode following fuel cell stack. (b) Second type with a battery charger and two diodes following both fuel cell stack and battery. (c) Third type with two diodes following both fuel cell stack and battery.

the battery needs to have the ability of high capacity and high rated current, which in turn will lead to a larger system weight or volume. In addition, the charging rate of the battery is not limited or controlled, which may cause unnecessary damage to the battery. Therefore, a battery charger unit is added in Fig. 8(b). Another difference between Fig. 8(a) and 8(b) is that the fuel cell system is always connected to the dc bus through a diode. The fuel cell system and the lithium-ion battery supply power to the motor together, and the dc bus voltage is clamped by the battery output voltage. According to the polarization characteristic curve of the fuel cell, the output terminal voltage of the fuel cell corresponds to its output current one-to-one. Under normal operating conditions, the output voltage of lithium-ion batteries changes within a narrow range. Therefore, the fuel cell system can be prevented from operating under too low- or too high-power conditions. At the same time, the battery charger is responsible for controlling the charging current rate and charging time. Therefore, the battery is also protected to extend its service life. To further simplify the operating principle, Fig. 8(c) is proposed. In this structure, the fuel cell system and the battery are both connected with the dc bus through a diode. In [39], the propulsion system integrates an open cathode, metal bipolar plates PEM fuel cell stack, with fan, from the manufacturer BCH, model TH-200. Meanwhile, six KOKAM Ultra High Energy NMC Lipo cells are also adopted. The results show that to guarantee a suitable joint operation of the fuel cell and the battery, careful design, selection, and development of both components are required. However, compared with pure fuel cell systems and series hybrid propulsion systems, both the dynamic performance and fault-tolerant ability are improved.

So far, passive parallel hybrid systems can be seen in many research papers [40] and various commercial vehicles, such as Honda Insight, Civic, and Accord hybrids [41]. Verstraete *et al.* [42] conducted an experimental study to better understand passive power plants, including the importance of battery and system energy management for proper system integration. The results showed that the battery played a vital role

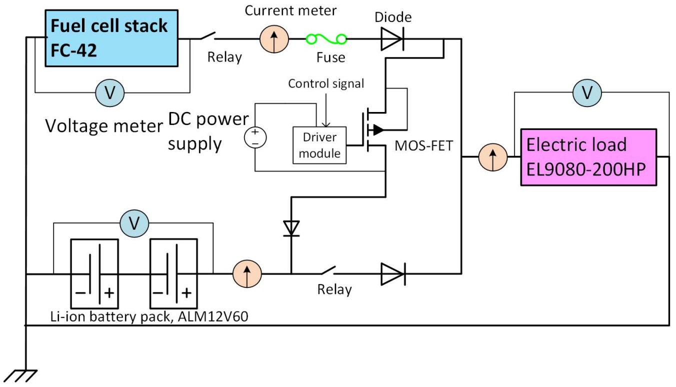


Fig. 9. Ground test bench of the passive parallel hybrid system [43].

in the dynamic load response, and the dynamic performance greatly depended on the battery's capacity and rated current. When the load changes rapidly, the performance of a battery with a small capacity but a large rated current is similar to that of a battery with a large capacity but a small rated current. This finding can be regarded as design guidance for application engineers. Some other researchers also use ground test benches to evaluate the performance of passive parallel hybrid power systems [43], [44], including the static behavior, dynamic behavior, and battery charging characteristics of the entire system. The related picture of the ground test bench is shown in Fig. 9. The results verified that the passive configuration could achieve good system efficiency and good response to dynamic loads and could charge the onboard battery through a simple circuit without a dc–dc converter.

In addition to the passive parallel hybrid power system, the active parallel hybrid power system has also received a lot of research attention. Fig. 10 gives a comprehensive description of the various active structures [45]. In this figure, one of the black boxes represents the fuel cell system, and the other represents the battery. In structure A, the battery is directly connected to the fuel cell system, and then, the dc–dc converter is placed between the dc bus and the load (i.e., the dc–ac converter in the figure). The battery pack as an energy buffer is responsible for transient loads. At the same time, it also functions as part of the load in a steady state. The output power of the fuel cell system is not controlled. Whenever the output voltage of the battery is lower than that of the fuel cell, the battery is charged. In this case, the dc–dc converter needs to handle all the power from two sources, which leads to an intensive current design. In structure B, the fuel cell system is connected to the battery through a dc–dc converter, which means that the high-voltage battery needs to match the dc bus voltage. There are many similar characteristics between structures A and B. For example, the batteries in both structures are directly coupled to the dc bus, which enables the power system to respond quickly to load transients. However, this also means that the process of discharging and charging the battery is uncontrollable. Therefore, the battery may be overcharged or overdischarged, thereby accelerating battery aging. Moreover, since the dc bus voltage is determined by the battery output voltage, it is difficult to select a suitable battery pack for UAVs. As for structure C, it is the opposite of structure B. The dc–dc converter is placed at the end of the battery, and the fuel cell system is directly connected in parallel with the front-end dc–dc converter. Through this structure, the discharge and charging of the battery can be well controlled. Therefore, the battery life is prolonged and the current ripple of the fuel cell is eliminated. However, the power response of the fuel cell system is poor, which limits the dynamic performance of the entire system. Moreover, when the hybrid power system is applied to high-voltage operating conditions, an additional dc–dc converter is required, which will cause an additional cost. In structure D, both the fuel cell system and the battery are connected through a dc–dc converter. With the help of a dc–dc converter, the power sharing between these two power sources can be precisely controlled. The discharge and charging of the battery are also well-controlled, which can ensure that the battery is always working in an appropriate state. Moreover, in this structure, the selection of the fuel cell system and the battery is more convenient than that of the other three structures. However, since the battery is not directly connected to the dc bus, the dynamic performance of the entire system may be degraded to a certain extent. To solve this problem, appropriate EMSs and corresponding control algorithms need to be carefully designed. Unfortunately, the cost of the entire system will become higher and the reliability will degrade. In order to validate the abovementioned active architectures, a 1.5-kW prototype is built with a 1.2-kW fuel cell and 36-V 105-Ah lead-acid battery. Taking architecture D as an example, due to the dc–dc converters, it can emulate all the working modes, which are similar to another three architectures. The results show that this architecture maintains the best flexibility and the highest efficiency. However, its operation complexity is unsatisfactory. Moreover, compared with the passive hybrid propulsion system, when they both have the same power sources and loads, the total system weight and fault-tolerant ability of the active hybrid propulsion system are both unsatisfactory. Fig. 11 gives a clear spider diagram to evaluate the advantages and disadvantages of the above four active structures.

In summary, the above two configurations have their advantages and disadvantages. Due to the control and management strategies of related converters, the active configuration allows the selection and operation of fuel cells and batteries to be decoupled. In addition, due to the well-controlled dc–dc converters, each power supply can be precisely controlled, and the power sharing between different power supplies is more appropriate. This means that both the fuel cell and the battery can work under optimal conditions. Therefore, the lifetime of the entire system may be extended to its theoretical maximum. However, it still needs to be noted that these well-controlled converters also bring many shortcomings, such as low reliability due to more complex system topology and control; reduced system efficiency due to multilevel energy conversion; and larger volume and weight.

For the passive configuration, it has the advantages of higher efficiency, lower cost, and simple architecture. However, it cannot achieve active power distribution and control among multiple power sources, which may cause the fuel cell or battery pack to be in poor working condition. On the other

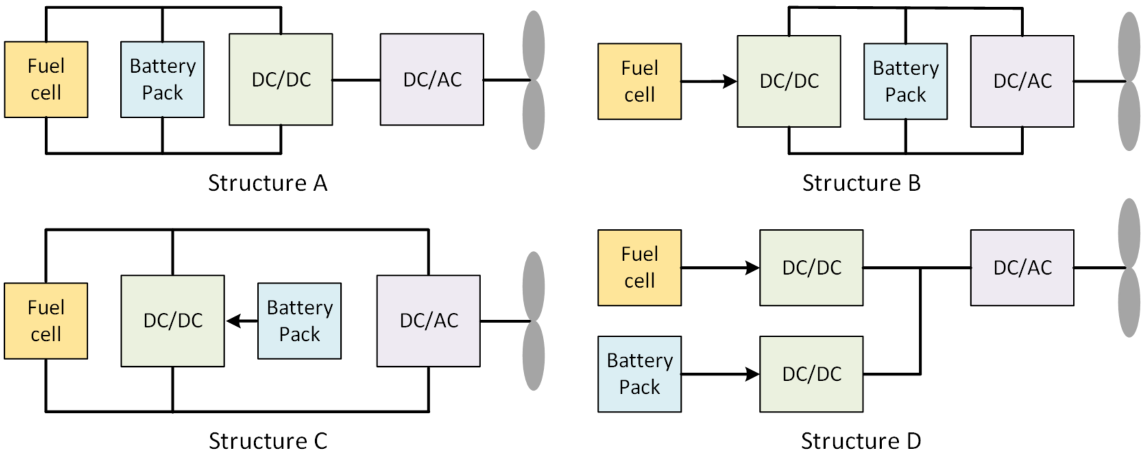


Fig. 10. Different active parallel hybrid power system structures [45].

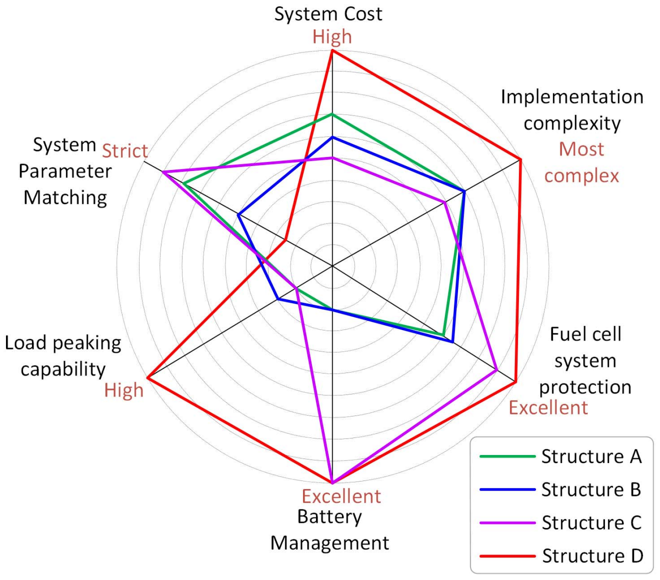


Fig. 11. Spider plot for evaluation of four different active parallel hybrid structures.

hand, to meet the performance required under specific tasks, fuel cells and battery packs need to be carefully designed and selected. When choosing the battery packs, a tradeoff must be made between the battery capability, boost-power availability, battery mass, and mission endurance. Therefore, the entire design process may become more complicated. Table I gives a detailed and comprehensive comparison between the active configuration and the passive configuration [39].

D. Discussion and Future Prospect

In general, the pure fuel cell power propulsion system is the simplest, but it cannot adapt to various load requirements. This means that the UAV cannot obtain the best performance, and the lifetime of the fuel cell system will drop sharply. As for the series configuration, it is slightly more complicated than the pure fuel cell system but has a better performance. Unfortunately, due to the characteristics of the two-stage conversion, its energy conversion efficiency is low. In contrast, the parallel configuration may perform best. Different sources have their advantages, such as high power density, high energy density, fast response, high reliability, and long lifetime. Therefore, when different types of power supplies are used in a parallel structure, this structure can combine their respective excellent characteristics to meet various load requirements, especially under severe conditions. In addition, the parallel configuration also has the best fault tolerance. Table II gives a brief comparison of pure, series hybrid, and parallel hybrid systems, focusing on complexity, efficiency, fault tolerance, dynamic performance, and weight. From this table, it can be found that the parallel configuration will be more beneficial to fuel cell UAVs in future development.

III. EMSS FOR FUEL CELL UAVS

As mentioned in Section II, the fuel cells are always hybrid with other power sources to complete a flight due to their slow response. Verstraete *et al.* [42] tested a fuel cell/battery propulsion system for UAV and indicated that the battery plays a crucial role in the response to dynamic load change and the system response is strongly influenced by the battery's capacity and current rating. The hybridization of different power sources brings power allocation problems; thus, EMSs are desired. According to [46]–[48], the goal of the fuel cell hybrid system EMS can be threefold: first, to guarantee that the fuel cell can supply stable or optimal power to the load; second, to exploit the advantages of different power sources regarding their working characteristic, hybrid construction, and flight factor; and third, to achieve a comprehensive energy management optimization to prolong the lifespan of the power sources and improve the system durability, stability, and overall efficiency.

The modeling methods are quite important for the design of EMS for fuel cell UAVs. According to the abovementioned goals of the fuel cell hybrid system's EMS, the power allocation model of the hybrid system is the basic requirement [101]. However, this model ignores the specific characteristics of components, such as fuel cell systems, batteries, and power electronics. Therefore, it is not easy to propose a satisfactory EMS method only based on this model. To synchronously obtain multiple objections, for example, high energy efficiency,

TABLE I

COMPARISON BETWEEN ACTIVE AND PASSIVE FUEL CELL/BATTERY HYBRID POWER SYSTEM [72]

	Advantages	Disadvantages
Active configuration	✧ Decoupling of sizing and operating conditions on batteries and fuel cell	✧ More complex system topology ✧ Losses in the DC-DC converters
	✧ More precise control of the power system	✧ Higher system cost ✧ Higher weight and volume
Passive configuration	✧ Lower losses ✧ Reduced cost ✧ Simpler architecture, lower risk of failure ✧ Lower weight and volume	✧ Active power control is not possible. The fuel cell operates at the voltage set by batteries. ✧ Careful design and integration of fuel cell system and batteries to fit the requirements of the load is needed

TABLE II

COMPARISONS AMONG PURE, SERIES HYBRID, AND PARALLEL POWER SYSTEMS

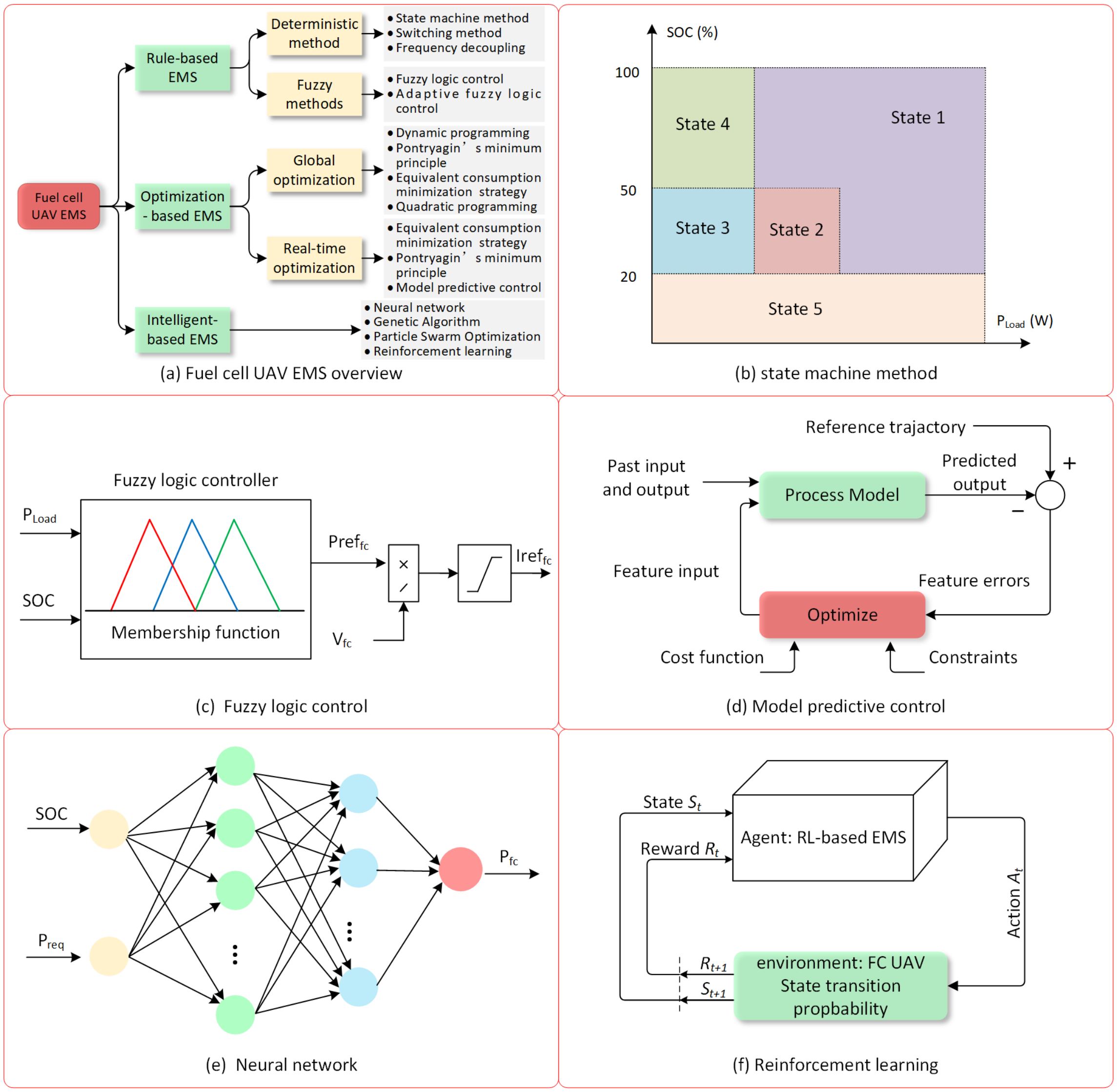
Configurations	Complexity	Efficiency (low power)	Efficiency (high power)	Fault tolerance	Dynamic performance	Weight
The pure fuel cell system	Low	Low	Medium	Medium	Low	Medium
Series hybrid power system	Medium	Medium	Low	Low	Medium	High
Parallel hybrid power system	High	High	High	High	High	Low

high economical efficiency, and long lifespan of fuel cell stack and battery, the specific models should be given and embedded into the framework of the EMS method. In this article, let us take the specific models of the fuel cell stack as an example, which can be divided into two categories, physics-based and data-driven models [102]. Since the fuel cell stack is a typical multiphase system, many specific models are proposed and embedded into the framework of the EMS method, for example, the efficiency model [103] and the lifetime degradation model [105], [107]. Compared with these specific models, the multiphase model can present more details of the fuel cell stack [106]. With the help of an advanced computation platform and efficient modeling method, multiphase models could be a potential research trend in the future.

Furthermore, according to the power system structure, the EMS can be divided into passive and active EMS. For the passive power system shown in Fig. 8, there is no dc–dc converter to control the power flow, and the power delivered by the fuel cell and the battery is determined by the load power, voltage of the fuel cell, and the battery. The passive EMS has the advantages of simplicity, weight reduction, and power loss reduction associated with the power converter, and it has been applied in fuel cell UAVs. For example, the passive EMS is applied to a tail-sitter hybrid lift UAV, which is powered by the fuel cell and lithium battery [49]. Although passive EMS is easy to be implemented, it cannot utilize the different characteristics of the power sources, which results in low efficiency. Also, the passive EMS cannot maintain the minimum SOC of the lithium battery, which will accelerate the degradation of the battery. In this article, we will focus on active EMS. Generally, the EMS methods can be categorized into rule-, optimization-, and intelligent-based methods, which are shown in Fig. 12.

A. Rule-Based EMS

Rule-based methods, such as state machines and fuzzy logic control, are widely used in EMS due to their simplicity, reliability, and computation efficiency advantages. State machine EMS divides the system into different states according to the load power and battery's SOC with corresponding control actions, which is the most used rule-based method. In [50], a rule-based method is proposed for a low-speed long-endurance UAV powered by fuel cell, photovoltaic (PV), and battery. Six sectors are identified based on the required power and SOC of the battery, which can ensure flight endurance and maintain an appropriate SOC. Similarly, a state machine control, which divides the control area into five states, for fuel cell UAV is developed in [51]. A rapid control prototype is built to testify simulation result, and the overall efficiency is more than 90% under different initial SOC states with the proposed method. To ensure that the energy utility rate difference of the fuel cell and the battery are controlled in an acceptable range when the fuel consumption is the least, a rule-based dynamic balance EMS is proposed [52]. Three states are set based on the difference between SOC and the remaining hydrogen rate. Under the proposed scheme, the reliability of the power system is improved as no power sources will be depleted in advance. Moreover, simulations and experimental tests are carried out to testify to the proposed method. Results validated that the method can ensure good performance under different load profiles. In [53], a power and energy management system for fuel cell UAV is developed, and the state machine is applied for energy management. The system operation is divided into three states: start-up state, charging state, and high power state based on the battery terminal voltage and dc bus current. Besides, the EMS is coupled with the fuel cell compressor



(a) Fuel cell UAV EMS overview (b) state machine method (c) Fuzzy logic control (d) Model predictive control (e) Neural network (f) Reinforcement learning

Fig. 12. Detailed structures of some commonly used EMS methods for fuel cell UAVs. (a) Fuel cell UAV EMS overview. (b) State machine method. (c) Fuzzy logic control. (d) MPC. (e) NN. (f) RL.

optimal power control, which achieved 2.6% energy saving compared with the constant compressor power.

Unlike the precisely deterministic method such as state machine, the fuzzy logic control uses the approximate way rather than the precise way, which is robust to system uncertainties. To realize online EMS, an online fuzzy logic strategy for a fuel cell/battery hybrid powered UAV is proposed [54]. The pulsed-power profile is implemented to evaluate the effectiveness and real-time feature of the proposed method. Besides, comparisons are made with the passive, state machine control methods under different flight missions. Experiment results indicate that the online fuzzy strategy gets the best performance considering the fuel consumption. Aiming at the high-efficiency operation of fuel cells, a fuzzy logic controller for a 1.2-kW fuel cell/battery hybrid system is developed in [55]. A 40-min flight scenario that includes five flight phases is implemented in the simulation and hardware-in-the-loop (HIL) experiment. Similarly, the fuzzy logic control is applied in a fuel cell/battery hybrid system to keep the fuel cell operating in a high-efficiency area with an affordable power slope [56]. Simulations are implemented under NEDC, UUDS, and user-defined driving conditions. Compared with the deterministic method, the proposed method gets higher efficiency. To get a better fuel economy, an optimized fuzzy logic control for a fuel cell/battery hybrid vehicle is proposed [57], and the genetic algorithm is used to find the optimal parameters of the controller. Simulation results indicate that the hydrogen consumption of the optimized fuzzy logic controller has been reduced by 22% from the conventional fuzzy logic controller. To ensure a longer endurance, a fuzzy state machine (FSM) strategy is proposed for PV/FC/battery hybrid electric UAV [58], where the fuzzy logic control deals with the power split between the fuel cell and battery and the state machine deal with the power flow of PV and battery. To ensure long endurance, the fuel cell gets the low priority to supply power to the system. Under the FSM strategy, 26.7% of the hydrogen fuel is saved compared with constrained thermostat control (CTC).

Besides the state machine and fuzzy logic, there are also other rule-based methods, such as switching technique, if–then rules, and frequency decoupling. To prolong the flight endurance, a switching technique for a fuel cell/solar cell (with a battery) hybrid UAV is proposed in [47]. To meet the load variation during the flight, the two power sources are controlled by a solid-state relay to decide which one or both output power. Such a mechanism is tested throughout a 1.5-h flight, and the system stability is guaranteed. Similarly, switching control logic is designed in [59] for a fuel cell/PV hybrid system. In [60], a fuel cell/LiPo battery hybrid system is built to evaluate the performance of three architecture models. If–then rule-based management is designed, which takes the battery operating voltage, fuel cell current, state of the fill, and charge rates in the hydrogen cylinder and battery SOC into account. Both the ground and flight tests are carried out to select the hybridization scenario and the battery. Based on the fact that the fuel cell's dynamic responsibility is slower than battery and supercapacitor, researchers proposed frequency decoupling methods for hybrid EMS. Specifically, the fuel cell responds to the low-frequency power, whereas the battery/supercapacitor will deal with the high-frequency power demand [61]. Under such a method, the SOC of the battery will keep in a narrow range since the mean energy of the battery is close to zero. In [62], two frequency decoupling methods: Wiener filter and wavelet transform for a fuel cell/ultracapacitor hybrid UAV are tested. The simulation results on a 1-kW level system indicate that the Wiener filter gets a better performance considering the mean high-frequency component, efficiency, and mean SOC value. In [63], a frequency separation rule-based for a fuel cell/battery-powered quadcopter is proposed, which enables the energy sources to be close to their nominal operating points and thus increases their service life. Besides, the SOC of the battery keeps in an acceptable range compared with the rule-based strategy that lets the fuel cell output a constant power, and 3% hydrogen saving is achieved by an equivalent consumption minimization strategy (ECMS). In that reference, the flight data are used for simulation verification.

To investigate the different EMS's effects, a comparative study of EMS for a fuel cell hybrid emergency power system of more electric aircraft is given in [64]. Six EMSs, including state machine control, rule-based fuzzy logic, classical proportional–integral (PI) control, frequency decoupling, fuzzy logic, and ECMS, are compared based on simulations and experiments carried out on a 14-kW fuel cell/battery/ultracapacitor hybrid system. The hydrogen consumption, overall system efficiency, scope of the battery/supercapacitor SOC, and life cycle are compared. Results indicate that the state machine control provides slightly better efficiency and stress on the battery and ultracapacitor. The frequency decoupling and fuzzy logic achieved the lowest fuel cell stress and the classical PI control consumes the least hydrogen. Although the rule-based methods are simple and reliable, experiences are required to design an acceptable EMS, and the optimal solution can hardly be reached. Thus, optimization-based methods are proposed to ensure the system working at its optimal points.

B. Optimization-Based Methods

Different from the rule-based method, the optimization-based methods can be designed to find the optimal result the designer wants to achieve, for example: to consume less hydrogen and assure a long lifespan. Based on the system power flow and constraints, the objection function will be built and the optimization method will be deployed to find the optimal solution.

Generally, the optimization-based EMS can be categorized into offline (global) and online (local) methods. The offline EMS, such as dynamic programming, linear programming, and quadratic programming [56], utilizes the known load profile to provide a globally optimal solution. However, the load profile in real missions is unknown in most cases, and thus, these methods can only be applied offline and are often set as a benchmark to evaluate other methods. Dynamic programming is used in [65] for a fuel cell/battery hybrid UAV to determine the optimal power flow that guarantees a long-endurance flight given the flight path. Four test conditions, steady level, turbulent level flight, cyclic power mission, and high power climb, are used to test the EMS. Simulation results indicate that the hybridization can decouple the aircraft constraint from the aircraft energy requirements, which can be beneficial to improve the performance through the proper integrated design process.

Pontryagin's minimum principle (PMP) as one of the online EMS methods tries to find a globally optimal solution by transforming the global optimization problem into a series of minimal values and solving one minimal value each time [65]. To realize online optimization, an adaptive EMS based on PMP for fuel cell/battery hybrid vehicles is proposed in [66]. To realize online driving cycle prediction, the PSO-SVM-based driving pattern classifier is first built and an improved Markov-based velocity predictor is applied to predict the driving behavior under different driven patterns. Simulation results show that 4% hydrogen is saved compared with the rule-based method, and the fuel cell average power change rate is relatively low, which is beneficial to its durability. Similarly, a real-time PMP EMS for fuel cell buses is developed [67], and over 20% hydrogen saving is achieved compared with the rule-based method. It should be noted that the real-time PMP is realized by a DBSCAN clustering method that matches the current driving segment based on the history data. Nevertheless, the proposed method can only work for applications that have a fixed driving cycle such as buses and trains. Aiming at optimizing the fuel economy and durability, an EMS based on PMP satisfactory optimization for fuel cell hybrid systems is proposed [68]. The experimental result indicates that the proposed method can significantly reduce the fuel cell output power fluctuation while preserving the similar hydrogen consumption to the standard PMP method. To test the character of the existing EMS methods, the fuzzy logic, DP, PMP, and improved PMP for a fixed-wing furl cell UAV through simulation based on a given load profile are compared [69]. It is found that the fuzzy logic is robust, but with higher hydrogen consumption, the improved PMP maintains the lowest fuel cell output power rate and saves 5.4% hydrogen compared with fuzzy logic.

In conclusion, both the DP and PMP can get a global optimal solution for the system, whereas the requirement for the driving cycle information makes them only suitable for the systems with a fixed route. Thus, local optimization methods, such as ECMS and model predictive control (MPC), are proposed. The ECMS is an instantaneous optimization strategy that calculates the control variable by minimizing the equivalent hydrogen consumption.

Generally, the ECMS uses a predetermined factor to estimate equivalent consumptions online, which cannot guarantee the SOC in the acceptable range. To address this problem, the adaptive-ECMS has been proposed. For the sake of safe landing for aircraft, a fuzzy logic-based ECMS (F-ECMS) method is proposed to improve the power system efficiency and keep the SOC of the battery in an appropriate range [70]. Two test cases are simulated, and the comparisons are made with conventional ECMS and adaptive ECMS. Results show that the F-ECMS can balance fuel consumption and SOC. To decrease the hydrogen consumption and increase the durability of the power sources, an ECMS for fuel cell/ battery and ultracapacitor hybrid system is developed [71]. Under the designed controller, the battery is worked as the main source, the fuel cell is operated to find the maximum efficiency point and the ultracapacitor is dedicated to providing the peak power. Simulation results indicate that the proposed method achieves a smooth fuel cell current and saves 2.16% hydrogen compared with the rule-based method. In [72], an adaptive multimode MPC for fuel cell hybrid vehicles to reduce fuel consumption and improve fuel cell durability. Driving segments obtained by the Markov pattern recognizer are taken into consideration to tune the controller. Simulation results under different driving scenarios show that 87% of fuel cell power transient is reduced and 2% of hydrogen is saved compared with the single-mode benchmark strategy. To test the influence of the velocity forecasting method, three methods, including generalized exponentially varying, Markov chain, and neural networks (NNs) of velocity predictors for MPC-based EMS of a hybrid electrical vehicle, are compared [73]. It is found that the NN predictor can get the highest accuracy. Moreover, with the prediction results of NN, the MPC can save 7% more hydrogen than the ECMS. It should be noticed that the performance of MPC depends on the power reference provided in each prediction result, and thus, precision prediction algorithms are needed to guarantee its performance.

C. Intelligent-Based Methods

For the optimization-based method, there is a tradeoff between precision and computation burden. To address this dilemma, intelligent-based methods, such as NN and reinforcement learning (RL), have drawn research attention recently. To improve service durability and fuel economy, a multilayer perceptron is adopted for driving pattern recognition, and then, a fuzzy energy management controller is used for power allocation for a fuel cell/ultracapacitor system [74]. Moreover, a genetic algorithm is utilized to optimize the critical parameter, thus prolonging the fuel cell lifetime and reducing hydrogen consumption. Simulation results indicate that the proposed method is the potential to be implemented online. To avoid the start–stop and rapid load change of fuel cells, an NN optimized by the genetic algorithm is proposed for the fuel cell hybrid vehicle [75]. Through the optimization of the genetic algorithm, the NN can be trained pertinently, and the trained network can consciously avoid specific outputs according to the requirement. Simulation shows that the start–stop of fuel cells has been reduced compared with NN and ECMS. Besides, the fuel consumption is close to the DP result. In the framework of RL, the RL agent receives the current state S_t and reward R_t from the environment and then determines a proper action A_t to function on the environment, and then, the environment will feedback S_{t+1} and R_{t+1} to the agent. The process [which is shown in Fig. 12(f)] will be continued until the agent finds a proper strategy according to the maximum accumulative reward.

To realize real-time application and approximate global optimization, an EMS based on K-nearest neighbor (KNN) and RL is proposed for fuel cell hybrid vehicles. The KNN is used to predict the long-term average speed of the future driving segment, whereas the RL is responsible for the global optimal approximation [76]. Simulation results indicate that 6.14% of fuel can be saved and the start–stop times of fuel cells are reduced by 21.7% compared with the rule-based method. In [77], an RL-based algorithm using an ECMS for a fuel cell/ battery, ultracapacitor hybrid vehicle is proposed. The simulation result under different driving cycles indicates that the equivalent fuel consumption of the RL-based method is less than that of ECMS. Moreover, the computation efficiency of the RL-based method is higher than that of the DP method. To improve the overall efficiency of a fuel cell/battery hybrid vehicle, an improved Q-learning-based method that takes the power source and converter's efficiency into consideration is proposed [78]. HIL experiment and on-road test show that the overall efficiency reaches 52% under the proposed strategy, which gains 8% higher than that of the state machine. To ensure long endurance, an improved double Q learning for the energy management of Hybrid UAVs is proposed [79], [100]. Plenty of flight data is used to train the model, and the results indicate that the method has stronger robustness and convergence speed. Besides, comparisons are made with the dynamic programming and rule-based methods. Results indicate that when the RL method has been well trained offline, it can be implemented in real time without sacrificing many functions in fuel and economical saving compared with the DP. Compared with the rule-based method, 20% of fuel saving is achieved. Although the intelligent methods have the advantages of being model-free, the high requirement of data and high computation burden make it hard for online optimization. Until now, there is no such method that has been applied in the fuel cell UAV online optimization.

D. Discussion and Future Prospect

To better illustrate the EMS for fuel cell UAVs, their features are listed in Table III. Currently, rule-based methods are mostly used in industry due to their simplicity and reliability. Although the optimization- and intelligent-based methods

TABLE III
SUMMARY TABLE OF EMS FOR FUEL CELL UAV

Method	Objective	Sources	Verification Methods	Remarks	Ref.
State machine	To improve the system efficiency	Fuel cell and battery	Rapid control prototype	Overall efficiency is more than 90% under different initial SOC states with the proposed method	[51]
Rule-based	To balance the rate of fuel can SOC	Fuel cell and battery	Ground test platform	The reliability of the power system is improved as no power sources will be depleted in advance.	[52]
State machine	To do FC system power management	Fuel cell and battery	simulation	EMS is coupled with the fuel cell compressor optimal power control, which identified 2.6% energy saving compared with the constant compressor power	[53]
Fuzzy logic	Online EMS for UAV	Fuel cell and battery	Test bench	Fuzzy strategy gets the best performance considering the fuel consumption compared with passive EMS and state machine	[54]
Fuzzy logic	Hydrogen saving and high efficiency	Fuel cell and battery	Simulation and HIL	The SOC will greatly influence the fuel working points, and low SOC induces a low efficiency	[55]
Fuzzy logic	To protect the fuel cell and ensure the efficiency	Fuel cell and battery	Simulation	Compared with the deterministic method, the proposed method gets higher efficiency.	[56]
Fuzzy logic	/	Fuel cell and battery	Experiment and simulation	Hydrogen consumption has been reduced by 22% to the conventional fuzzy logic controller	[57]
Fuzzy state machine	To ensure long-endurance	Fuel cell, PV, and battery	simulation	6.7% of the hydrogen fuel is saved compared with constrained thermostat control	[58]
Switching logic	To ensure long endurance	Fuel cell, PV, and battery	Real flight test	The system stability can be guaranteed	[47]
Frequency decoupling	/	Fuel cell and ultracapacitor	simulation	Wiener filter gets better performance than wavelet transform considering the mean high-frequency component, efficiency, and mean SOC value	[62]
Frequency decoupling and ECMS	To extend power sources' service life	Fuel cell and battery	Simulation with real flight data	The SOC of the battery keeps in an acceptable range compared with the rule-based strategy that lets the fuel cell output a constant power, and a 3% hydrogen saving is achieved	[63]
Dynamic programming	To ensure long-endurance	fuel cell and battery	simulation	Hybridization can decouple the aircraft constraint from the aircraft energy requirements, which can be beneficial to improve the performance through the proper integrated design process	[65]
PMP	Online optimization	Fuel cell and battery	simulation	4% hydrogen is saved compared with the rule-based method, and the fuel cell average power change rate is relatively low, which is beneficial to its durability	[66]
PMP	To improve service durability and fuel economy	Fuel cell and battery	Simulations and on-road experiment	20% hydrogen saving compared with the rule-based method	[67]
PMP satisfactory optimization	To improve service durability and fuel economy	Fuel cell and battery	Simulation with real tested data	The fuel cell output power fluctuation is reduced significantly and the hydrogen consumption is similar to the standard PMP method	[68]

TABLE III
(CONTINUED.) SUMMARY TABLE OF EMS FOR FUEL CELL UAV

Improved PMP	To ensure long-endurance	Fuel cell and battery	Simulation	A low power changing rate and 5.4% hydrogen saving are achieved compared with fuzzy logic	[69]
Fuzzy ECMS	To ensure the SOC is in a suitable range	ICE / battery	simulation	F-ECMS can balance fuel consumption and SOC	[70]
ECMS	To improve service durability and fuel economy	Fuel cell, battery, and capacitor	simulation	Achieves a smooth fuel cell current and saves 2.16% hydrogen compared with the rule-based method	[71]
Multi-mode MPC	To improve service durability and fuel economy	Fuel cell and battery	simulation	87% of fuel cell power transient are reduced and 2% hydrogen is saved compared with the single-mode benchmark strategy	[72]
MPC	To test the influence of the velocity forecasting method	ICE / battery	simulation	with the prediction results of NN, the MPC can save 7% more hydrogen than the ECMS	[73]
NN and fuzzy	To improve service durability and fuel economy	Fuel cell and ultracapacitor	simulation	the proposed framework can ensure the state of charge of SCs within the desired limit	[74]
GA optimized NN	To avoid the start-stop and rapid load change of fuel cell	Fuel cell and battery	simulation	start-stop of fuel cell has been reduced compared with NN and ECMS. Besides, the fuel consumption is close to the DP result	[75]
Reinforcement Learning	To realize real-time application and approximate global optimization	Fuel cell and battery	simulation	6.14% of fuel can be saved and the start-stop times of fuel cells are reduced by 21.7% compared with the rule-based method	[76]
Reinforcement Learning	To achieve low computation cost, optimal efficiency, and fuel economy	Fuel cell, ultra-capacitor, and attery	simulation	The equivalent fuel consumption of the RL-based method is less than that of ECMS. Moreover, the computation efficiency of the RL-based method is higher than the DP method	[77]
Improved Q-learning	To improve the overall efficiency	Fuel cell and battery	HIL experimental and on-road test	Overall efficiency reaches 52% under the proposed strategy, which gains 8% higher than that of the state machine.	[78]
Double Q-learning	To ensure long-endurance	ICE / battery	Simulation with test data	RL method can reduce the computation time without sacrificing many functions in fuel and economical savings compared with the DP	[79]

can ensure a longer flight and durability, more computational resources are needed; otherwise, the online EMS may sometimes not be guaranteed. The main difference between the rule-based method and the optimization-based method is that the optimization-based method is more dependent on the accuracy of modeling. If the model cannot be provided, it is difficult to implement the optimization-based methods, not to mention to get satisfactory results. However, if the system model can be obtained, the global optimization results can be easily gotten when compared with the rule-based methods. Furthermore, compared with intelligent methods, most optimization methods can be classified into the convex optimization group, which means that only one maximum or minimum value exists. While most intelligent-based methods have many extreme values and they can also be used to get satisfactory results without physical models. As for the real-time applications, most rule-based ESM methods could be used to manage the whole system's power flow online, whereas most optimization- and intelligent-based EMS methods could not be implemented in real time due to the heavy computation burden. To help these two kinds of methods be implemented online in the future, more efficient algorithms and advanced computation platforms should be improved. Besides, it can be seen from Table III that most of the existing methods are verified by simulations or HIL, but few researchers have applied their advanced EMS to the real fuel cell UAV. There is a gap between the simulation

Fig. 13. Potential applications of fuel cell UAVs.

and real application as the real flight is far more complicated. Besides, advanced methods such as RL are emerging in the application of fuel cell hybrid vehicles, whereas they have been rarely applied to fuel cell UAVs due to the complicated working condition and safety issues. Therefore, more ground or real flight tests with advanced EMS should be investigated to prompt the real implementation of EMS on UAVs. Regarding the power sources, most of the power system structures consist of fuel cells and batteries, whereas the performance of the battery may deteriorate at high altitudes, which is the case that high-altitude UAVs may encounter. Thus, it would be a good choice to install a supercapacitor to improve the performance in high altitude and cold weather since the energy stored in an ultracapacitor can be maintained at low temperatures.

IV. SPECIAL APPLICATIONS AND CONSIDERED DESIGN METHODS

Due to the development of academic research and industrial manufacturing, fuel cell UAVs can be used in almost all businesses, such as precision agriculture, delivery services, wildlife surveys, research, and rescue. As shown in Fig. 13, this briefly lists the potential applications of fuel cell UAVs. The application of UAVs in various fields is described in detail next.

In agriculture applications, people prefer to use UAVs to capture high-precision images above the fields [80]. After that, various image processing algorithms are used to obtain specific data. Those data can indicate the health information of crops and estimate the crop yield. UAVs can also be used for crop dusting and other tasks, such as weed detection, tillage analysis, and tillage mapping [81]. In urban service applications, UAVs play an important role in traffic monitoring. Compared with traditional methods, UVA is more flexible and more accurate and has a larger coverage area [82]. The traffic information obtained by UAVs will help people choose more suitable traffic routes. At the same time, because UAVs can obtain traffic information in real time, map data will also be updated in time to provide people with more accurate navigation information. In addition, some companies have used UVA for fast package delivery [4] or medical delivery, such as Google, Amazon, and JD. In terms of infrastructure, many facilities require regular maintenance, which requires a large number of employees and machines to be deployed in a large work area. Today, UAVs can perform autonomous inspections on oil pipelines, signal towers, high-rise buildings, bridges, highways, dams, and so on [83], [84]. In terms of entertainment, DJI is one of the most famous companies, which allows people to take pictures in the air through UAVs. At the same time, many professional teams are conducting aerobatics and light shows through UAVs. In the military field, the application of UAVs is more common and mature than that in the civilian field. In reality, UAV technology was first developed for military activities, which can greatly protect the lives of soldiers. The famous military applications of UAVs include artillery guidance, reconnaissance flights, communication jammers, electronic warfare, antiship missile defense, and so on [85]. In the power field, more and more renewable

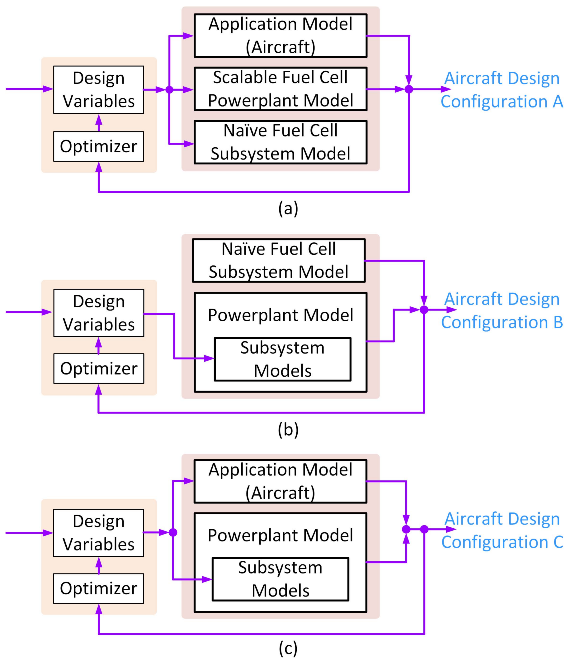


Fig. 14. Three design processes were used in the previous study [93]. (a) Configuration A. (b) Configuration B. (c) Configuration C.

energy power generation equipment is integrated into the grid, such as solar panel power stations and wind power plants. UAVs have been used to estimate the dust accumulation on solar panels [86] and detect the fault of the wind turbine blade surface [87]. With the maturity of high-voltage transmission technology, UAVs are also used for the inspection of power lines [88]. Natural disasters also pose a threat to people's lives and properties. Therefore, it is very important to use UAVs to perform regular monitoring and data collection in forests, volcanoes, and even the atmosphere to help us develop effective prevention strategies [89]. Moreover, when unexpected disasters occur, the communication infrastructure may be destroyed. In this case, the UAV can become a signal relay station and quickly provide data connections [5]. If the damaged area is large, UAVs equipped with infrared cameras can also be used to detect life signals. In the field of environmental protection and scientific research, UAVs are also regarded as an effective tool. When a specific sensor is installed on the UAV, it can perform real-time monitoring of pollutant gas diffusion rate [90], water pollution [91], and biological migration. Governments around the world are paying more and more attention to these activities. In addition, when working in the field, UAVs can be used for data collection in hazardous environments.

Through the abovementioned various UAV application cases and the various advantages of fuel cell UAVs, it can be seen that the demand for fuel cell UAVs will increase greatly. To better satisfy this demand, a mature design process for fuel cell UAVs is important. The rest of this section will focus on the general design procedures for most fuel cell UAVs and detailed design methods for specific applications. In the early days, there are few reports about fuel cell UAV design methods; therefore, the design methods for conventional airplanes are usually made as a reference. At present, three design methods are mainly used [92].

First, the proposed design process focuses on a predesigned fuel cell power plant, as shown in Fig. 14(a) [93]. This is the most convenient method because the power plant can be considered an integral component. After the fuel cell power plant is selected, it should be combined with the parametric aircraft model. However, because the characteristics of the power plant are derived from the automotive fuel cell, the fuel cell subsystem or component-level model cannot be obtained. Therefore, the disadvantage is that the interaction between the fuel cell components cannot be modeled in detail, and the low-level information about the power plant cannot be provided for the implementation of subsequent tasks.

The second design method refers to the design of the fuel cell and its subsystems are independent of the design of aircraft [94]. Its configuration is shown in Fig. 14(b). In this way, the fuel cell power plant can achieve the required specific energy, and the interaction of the components in the subsystem can also be estimated clearly. The disadvantage of this method is that it does not consider the interaction between the fuel cell and the aircraft.

The last method is the integration of power plant and aircraft [95]. As shown in Fig. 14(c), the aircraft level and the fuel cell power plant level are performed simultaneously. In this way, the aircraft and fuel cell power plants can be optimized at the same time, which means that the final power plants will be more suitable for specific applications. However, it requires more design space, which will further lead to greater complexity and higher computational costs.

Through the review of the above three design processes, it can be found that the last one may be more competitive. To solve its disadvantages of high complexity and high computational cost, many researchers have conducted a lot of research on it. Next, three specific design procedures for fuel cell UAVs will be introduced in detail.

A. Specific Design for High-Altitude Fuel Cell UAV

For a high-altitude fuel cell UAV, the desired altitude is usually above 10 km, which means that it will take longer to climb. Therefore, generally speaking, the fuel cell system needs to be used as the main power source, and the battery is only used for starting and powering the control board. The design process of the high-altitude fuel cell UAV is given in the flowchart, as shown in Fig. 15.

First, it is necessary to obtain or determine the main characteristics of the UAV, such as the total mass of the fuselage, the expected service ceiling, the lift coefficient, and the wing load. Then, simple aerodynamic principles need to be used to calculate the minimum power at the predesigned service ceiling. Third, the power conversion efficiency of each component should be estimated empirically. Through all these efficiency values, the total efficiency of the power system can also be obtained. Applying this total efficiency value to the equation shown in the first stage, the relationship between the mass of the UAV and the minimum fuel cell power is obtained. This equation gives the upper limit of the total mass of the UAV. Next, the fuel cell stack system and its BoP should be carefully selected. In this step, the rated power of the fuel cell

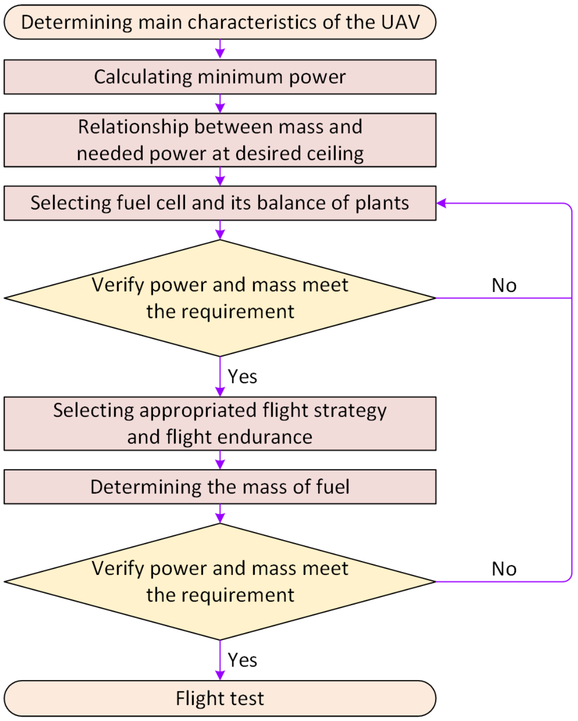


Fig. 15. Design flowchart of high-altitude fuel cell UAV [19].

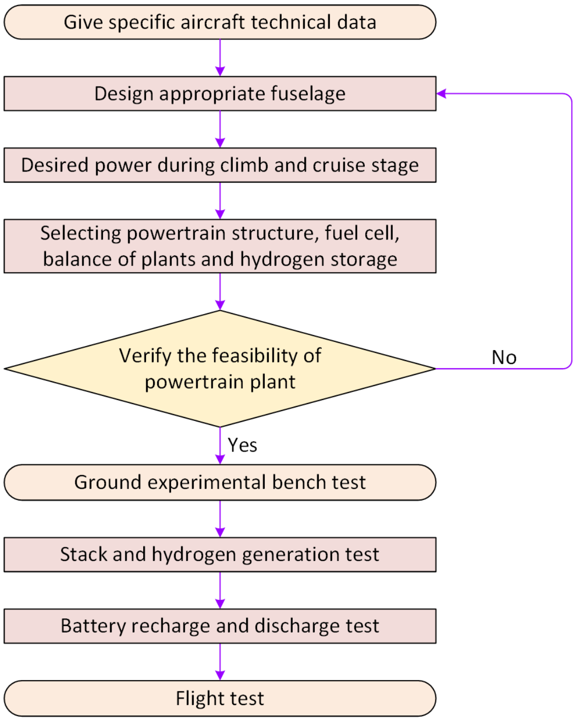


Fig. 16. Design flowchart of low-altitude fuel cell UAV [96].

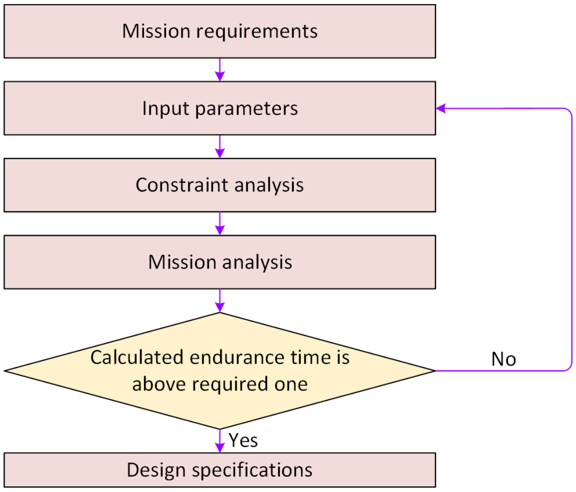


Fig. 17. Conceptual design process of small fuel cell UAV [97].

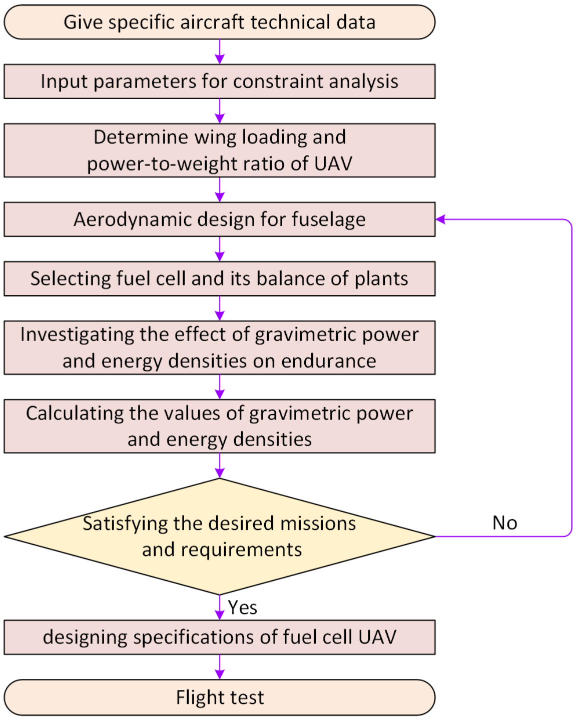


Fig. 18. Design flowchart of long-endurance fuel cell UAV [97].

system and the total mass of the UAV should be verified. Fifth, appropriate flight strategies should be carefully considered based on the predesigned flight endurance and other related specifications. Through this step, the amount and mass of hydrogen fuel can be determined. In terms of oxygen supply, there are two commonly used methods: air compressor and pure oxygen vessel. Comparatively speaking, the latter is more attractive than the former. If the latter is selected, we can also calculate the mass of the oxygen vessel. So far, the total mass of the entire fuel cell UAV has been obtained. Finally, we need to use the total mass obtained above to verify whether the rated power of the fuel cell meets the requirements and whether the total mass of the UAV is below the upper limit. If so, the whole process will end. If not, the iterative calculation is required. Based on the above steps, a detailed design procedure for a light fuel cell UAV that can achieve an altitude of 10 km can be found in [19].

B. Specific Design for Low-Altitude Fuel Cell UAV

Low-altitude UAVs prefer better dynamic performance and even do some stunts, such as rolls, spins, loops, and

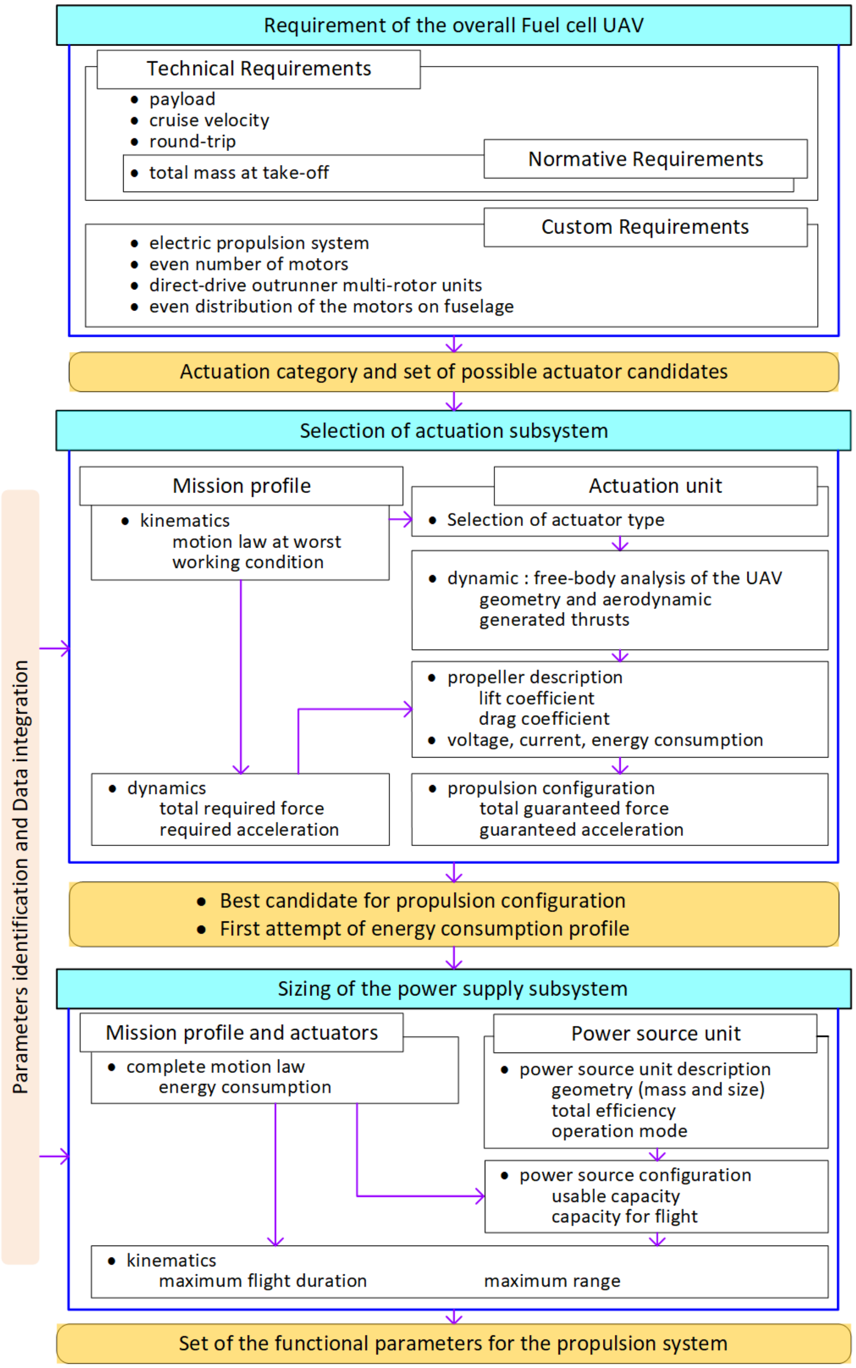


Fig. 19. Synthetic roadmap of the integrated functional design framework for the propulsion system identification [98].

Immelmann turns. Therefore, it is important to select an appropriate fuel cell system and battery pack. The function of the battery is not only the power source of the controller board but also the power source of the propulsion system. The design procedure of the low-altitude fuel cell UAVs is given by a flowchart, as shown in Fig. 16.

First, specific aircraft technical data should be given, such as wingspan, wing load, size, and maximum take-off load. Then, a suitable airframe needs to be considered, including wings, structure, and materials. It may have a great influence on the final flight performance. Third, according to the principles of aerodynamics, the power required for the climb stage and the cruise stage can be obtained separately. Next, we need to carefully select or design the powertrain structure, fuel cell stack system, battery pack, and even hydrogen storage methods. Fifth, the mass of the entire fuselage can be calculated to verify the feasibility of the power plant. If so, the payload can be calculated. If not, the iterative calculation is required. To better meet the dynamic operation, after the above conceptual design, some ground tests are needed, including stack and hydrogen production tests, and battery charging and discharging tests. Based on the above design steps, the detailed design procedure for low-altitude fuel cell UAVs can be found in [96].

C. Specific Design for Long-Endurance Fuel Cell UAV

For long-endurance fuel cell UAVs, sufficient energy is an important factor. Therefore, it is normal that a conceptual design process is executed for energy. Fig. 17 gives a brief flowchart for designing a long-endurance fuel cell UAV. It can be seen that it can be divided into three stages: missions and other parameters, constraint and mission analysis, feasibility verification, and design specifications. To illustrate this process more clearly, a detailed flowchart is given, as shown in Fig. 18.

First, similar to other specific fuel cell UAVs, the main characteristics of the UAV should be given, including total mass, flight altitude, and flight duration. Then, the input parameters of the constraint analysis can be determined empirically. Generally, these parameters include aspect ratio, efficiency, friction coefficient, speed ratio, and so on. Third, the parameters obtained in the second stage are used for constraint analysis, which will determine the wing load and power-to-weight ratio of the UAV. In practice, wing load and power-to-weight ratio are the two most important factors for UAVs, and they have a great influence on flight endurance and dynamic performance. Therefore, the aerodynamic design of the airframe should be better, and the choice of fuel cell system should be more cautious. Next, we can investigate the effect of gravimetric power and energy densities on endurance and calculate these two values. Finally, mission analysis can be performed based on the parameters obtained above. If all the requirements are met, the design specifications for fuel cell UAVs can be determined. If not, iterative computations will be needed. Based on the above design steps, the detailed design procedure of the long-endurance fuel cell UAV can be found in [97].

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D. Discussion and Future Prospect

In general, the design of the propulsion system of fuel cell UAVs should integrate different kinds of requirements. These requirements often include the demand of mission profile, power supply, and actuation subsystems. Besides, the constraints related to the technical requirement, normative requirement, and custom requirement should also be considered. Through analyzing the design process of different UAVs, it can be concluded that there are three main design stages: 1) the identification of the requirements for the overall UAV; 2) the selection of the actuation systems; and 3) the sizing of the power supply subsystem. A detailed explanation of these three stages is given in Fig. 19 [98]. From this figure, it can be found that every stage has its main tasks. The first stage is to determine the actuation and set of possible actuator candidates through the demand analysis of the overall UAV. The second stage is to determine the best candidate for propulsion configuration and make the first attempt at the energy consumption profile. The final stage is to determine the final functional parameter set for the propulsion system. Although there are many different applications and categories of UAVs, they all need to comply with the abovementioned design stages. The difference is that each type of UAV has a different design focus.

V. CONCLUSION

Fuel cell UAVs can be regarded as one of the most emerging technologies in the world. They may cause tremendous changes in the economy and society and greatly improve people's lives. Compared with other types of UAVs, fuel cell-powered UAVs have many advantages, which have attracted the attention of many researchers. However, due to the inherent disadvantages of fuel cell systems and some technological bottlenecks of the fuel cell electric propulsion systems, it is still difficult for fuel cell UAVs to have some satisfactory characteristics, including long endurance, high reliability, and extended lifespan.

In this work, we give a comprehensive review of some key technologies for the electric propulsion system of fuel cell UAVs. As one of the most important technologies, the electric propulsion architecture of the fuel cell UAVs is first given. The pure fuel cell architecture is simple to implement. Nevertheless, the overall efficiency and dynamic response of the pure fuel cell system are limited. Therefore, hybrid propulsion architectures are reviewed, including series hybrid architecture and parallel hybrid architecture. These hybrid architectures can combine the advantages of different power sources. However, due to the characteristics of the two-stage conversion, the energy conversion efficiency of the series hybrid system is low. By contrast, the parallel hybrid system is more efficient, but effective EMS is needed. As can be seen, the rule-based EMS methods are mostly used for fuel cell UAV applications. Although many advanced EMS methods have been proposed aiming to improve the flight endurance and reliability of fuel cell UAVs, online EMS is usually difficult to be guaranteed because of the large computational burden. In addition, most of the proposed advanced methods are just verified by simulation or HIL. Therefore, more ground or real flight tests with advanced EMS should be investigated to prompt the real implementation of EMS on UAVs. As for the different kinds of fuel cell UAVs, some detailed design procedures are given. In order to provide a design guideline for most kinds of fuel cell UAVs, a general systematic method is also provided. Each kind of UAV could be successfully designed by focusing on different aspects. According to the abovementioned analysis, the main conclusions can be made as follows.

1) Among kinds of propulsion architectures, the parallel hybrid power system shows a greater advantage. However, it is dependent on specific situations to select active or passive parallel hybrid power systems.
2) Optimization and intelligent-based EMS methods show more attractive prospects. However, the corresponding solving algorithms and hardware computation platform need to be developed.
3) For small and medium fuel cell UAVs, there is a general design procedure to follow. However, the UAVs with specific requirements need to emphasize some processes while ignoring others.

Furthermore, in the race for widespread applications of fuel cell UAVs and considering each technical challenge involved in the development of fuel cell electric propulsion systems, several critical issues and future directions are also listed as follows:

1) to propose innovative hybrid propulsion systems for fuel cell UAVs, considering the mini, medium, and large UAVs, such that the propulsion efficiency and reliability can be improved;
2) to develop a high power density and high-reliability converter for fuel cell UAVs, such that the total take-off weight of fuel cell UAVs can be reduced;
3) to develop advanced online EMSs for fuel cell UAVs, considering different applications, such that global optimal results can be obtained;
4) to design more efficient algorithms or develop a more powerful computation platform, such that advanced EMS methods can be implemented in real time;
5) to develop more detailed design guidelines for all kinds of fuel cell UAVs, such that as much as possible constraints can be considered in the design process;
6) to research advanced simulation and computation platforms for the propulsion system of fuel cell UAVs, such that the whole design process can be accomplished automatically.

REFERENCES

[1] P. Liu *et al.*, "A review of rotorcraft unmanned aerial vehicle (UAV) developments and applications in civil engineering," *Smart Struct. Syst*, vol. 13, no. 6, pp. 1065–1094, 2014.

[2] D. W. Casbeer, S.-M. Li, R. W. Beard, R. K. Mehra, and T. W. McLain, "Forest fire monitoring with multiple small UAVs," in *Proc. Amer. Control Conf.*, 2005, pp. 3530–3535.

[3] W. Jin, H. Ge, H. Du, and X. Xu, "A review on unmanned aerial vehicle remote sensing and its application," *Remote Sens. Inf.*, vol. 1, pp. 88–92, 2009.

[4] M. Hassanalian and A. Abdelkefi, "Classifications, applications, and design challenges of drones: A review," *Progr. Aerosp. Sci.*, vol. 91, pp. 99–131, May 2017.

[5] H. Shakhatreh *et al.*, "Unmanned aerial vehicles (UAVs): A survey on civil applications and key research challenges," *IEEE Access*, vol. 7, pp. 48572–48634, 2019.

[6] M. N. Boukoberine, Z. Zhou, and M. Benbouzid, "A critical review on unmanned aerial vehicles power supply and energy management: Solutions, strategies, and prospects," *Appl. Energy*, vol. 255, Dec. 2019, Art. no. 113823.

[7] *Global Military UAV Market Size to Hit $13bn by 2024 and Global Consumer UAV Market Size to Exceed $9bn by 2024*. Accessed: Sep. 30, 2019. [Online]. Available: https://www.gminsights.com/pressrelease/unmanned-aerial-vehicles-UAV-commercial-drone-market

[8] E. Bongermino, F. Mastrorocco, M. Tomaselli, V. G. Monopoli, and D. Naso, "Model and energy management system for a parallel hybrid electric unmanned aerial vehicle," in *Proc. IEEE 26th Int. Symp. Ind. Electron. (ISIE)*, Jun. 2017, pp. 1868–1873.

[9] T. Donateo and L. Spedicato, "Fuel economy of hybrid electric flight," *Appl. Energy*, vol. 206, no. 15, pp. 723–738, Nov. 2017.

[10] I. Burch and J. Gilchrist, "Survey of global activity to phase out internal combustion engine vehicles," Center Climate Protection, Santa Rosa, CA, USA, Tech. Rep., Sep. 2018.

[11] M. A. Hannan, F. A. Azidin, and A. Mohamed, "Hybrid electric vehicles and their challenges: A review," *Renew. Sustain. Energy Rev.*, vol. 29, pp. 135–150, Jan. 2014.

[12] A. Gong and D. Verstraete, "Fuel cell propulsion in small fixed-wing unmanned aerial vehicles: Current status and research needs," *Int. J. Hydrogen Energy*, vol. 42, no. 33, pp. 21311–21333, Aug. 2017.

[13] D. Verstraete, K. Lehmkuehler, and K. C. Wong, "Design of a fuel cell powered blended wing body UAV," in *Proc. ASME Int. Mech. Eng. Congr. Expo.*, 2012, pp. 621–629.

[14] *APOLLO 13 the Seventh Mission: The Third Lunar Landing Attempt*. Accessed: Apr. 1970. [Online]. Available: https://www.nasa.gov/topics/technology/hydrogen/hydrogen_2009.html

[15] Ó. González-Espasandín, T. J. Leo, and E. Navarro-Arévalo, "Fuel cells: A real option for unmanned aerial vehicles propulsion," *Sci. World J.*, vol. 2014, pp. 1–12, Jan. 2014.

[16] O. Z. Sharaf and M. F. Orhan, "An overview of fuel cell technology: Fundamentals and applications," *Renew. Sustain. Energy Rev.*, vol. 32, pp. 810–853, Apr. 2014.

[17] J. Renau *et al.*, "Use of fuel cell stacks to achieve high altitudes in light unmanned aerial vehicles," *Int. J. Hydrogen Energy*, vol. 40, no. 42, pp. 14573–14583, Nov. 2015.

[18] J. Wang, "Barriers of scaling-up fuel cells: Cost, durability and reliability," *Energy*, vol. 80, pp. 509–521, Feb. 2015.

[19] W. R. W. Daud, R. E. Rosli, E. H. Majlan, S. A. A. Hamid, R. Mohamed, and T. Husaini, "PEM fuel cell system control: A review," *Renew. Energy*, vol. 113, pp. 620–638, Dec. 2017.

[20] Y. Bicer and I. Dincer, "Life cycle evaluation of hydrogen and other potential fuels for aircrafts," *Int. J. Hydrogen Energy*, vol. 42, no. 16, pp. 10722–10738, Apr. 2017.

[21] E. Baharozu, G. Soykan, and M. B. Ozerdem, "Future aircraft concept in terms of energy efficiency and environmental factors," *Energy*, vol. 140, pp. 1368–1377, Dec. 2017.

[22] M. D. Fernandes *et al.*, "SOFC-APU systems for aircraft: A review," *Int. J. Hydrogen Energy*, vol. 43, no. 33, pp. 16311–16333, Aug. 2018.

[23] M. N. Boukoberine, Z. Zhou, and M. Benbouzid, "A critical review on unmanned aerial vehicles power supply and energy management: Solutions, strategies, and prospects," *Appl. Energy*, vol. 255, Dec. 2019, Art. no. 113823.

[24] T. H. Bradley, B. A. Moffitt, D. N. Mavris, and D. E. Parekh, "Development and experimental characterization of a fuel cell powered aircraft," *J. Power Sources*, vol. 171, no. 2, pp. 793–801, 2007.

[25] K. Swider-Lyons, M. Schuette, R. Stroman, J. Rodgers, G. Page, and J. Mackrell, "Liquid hydrogen fuel system for small unmanned air vehicles," in *Proc. 51st AIAA Aerosp. Sci. Meeting including Horizons Forum Aerosp. Expo.*, Jan. 2013, p. 467.

[26] T. Kim, "$NaBH_4$ (sodium borohydride) hydrogen generator with a volume-exchange fuel tank for small unmanned aerial vehicles powered by a PEM (proton exchange membrane) fuel cell," *Energy*, vol. 69, pp. 721–727, May 2014.

[27] H. Tawfik, Y. Hung, and D. Mahajan, "Metal bipolar plates for PEM fuel cell-a review," *J. Power Sources*, vol. 163, no. 2, pp. 755–767, 2007.

[28] A. Emadi, K. Rajashekara, S. S. Williamson, and S. M. Lukic, "Topological overview of hybrid electric and fuel cell vehicular power system architectures and configurations," *IEEE Trans. Veh. Technol.*, vol. 54, no. 3, pp. 763–770, May 2005.

[29] R. S. Wegeng, L. R. Pederson, W. E. TeGrotenhuis, and G. A. Whyatt, "Compact fuel processors for fuel cell powered automobiles based on microchannel technology," *Fuel Cells Bull.*, vol. 3, no. 28, pp. 8–13, Jan. 2001.

[30] F. G. Harmon, A. A. Frank, and J.-J. Chattot, "Conceptual design and simulation of a small hybrid-electric unmanned aerial vehicle," *J. Aircr.*, vol. 43, no. 5, pp. 1490–1498, Sep. 2006.

[31] C. Kim, E. NamGoong, S. Lee, T. Kim, and H. Kim, "Fuel economy optimization for parallel hybrid vehicles with CVT," *SAE transactions*, vol. no., pp. 2161–2167, 1999.

[32] P. Bubna, D. Brunner, J. J. Gangloff, S. G. Advani, and A. K. Prasad, "Analysis, operation and maintenance of a fuel cell/battery series-hybrid bus for urban transit applications," *J. Power Sources*, vol. 195, no. 12, pp. 3939–3949, Jun. 2010.

[33] F. Re, "Viability and state of the art of environmentally friendly aircraft taxiing systems," in *Proc. Electr. Syst. Aircr., Railway Ship Propuls.*, 2012, pp. 1–6.

[34] M. Harmats and D. Weihs, "Hybrid-propulsion high-altitude long-endurance remotely piloted vehicle," *J. Aircr.*, vol. 36, no. 2, pp. 321–331, Mar. 1999.

[35] Z. Ji, J. Qin, K. Cheng, F. Guo, S. Zhang, and P. Dong, "Thermodynamics analysis of a turbojet engine integrated with a fuel cell and steam injection for high-speed flight," *Energy*, vol. 185, pp. 190–201, Oct. 2019.

[36] P. Aguiar, D. Brett, and N. Brandon, "Solid oxide fuel cell/gas turbine hybrid system analysis for high-altitude long-endurance unmanned aerial vehicles," *Int. J. Hydrogen Energy*, vol. 33, no. 23, pp. 7214–7223, Dec. 2008.

[37] Z. Ji, J. Qin, K. Cheng, C. Dang, S. Zhang, and P. Dong, "Thermodynamic performance evaluation of a turbine-less jet engine integrated with solid oxide fuel cells for unmanned aerial vehicles," *Appl. Thermal Eng.*, vol. 160, Sep. 2019, Art. no. 114093.

[38] K. Rajashekara, J. Grieve, and D. Daggett, "Hybrid fuel cell power in aircraft," *IEEE Ind. Appl. Mag.*, vol. 14, no. 4, pp. 54–60, Jul. 2008.

[39] E. L. González *et al.*, "Experimental evaluation of a passive fuel cell/battery hybrid power system for an unmanned ground vehicle," *Int. J. Hydrogen Energy*, vol. 44, no. 25, pp. 12772–12782, May 2019.

[40] J. Bernard *et al.*, "Fuel cell/battery passive hybrid power source for electric powertrains," *J. Power Sources*, vol. 196, no. 14, pp. 5867–5872, Jul. 2011.

[41] K. Aoki, S. Kuroda, S. Kajiwara, H. Sato, and Y. Yamamoto, "Development of integrated motor assist hybrid system: Development of the 'insight' a personal hybrid coupe," *SAE Trans.*, vol. 109, no. 3, pp. 1883–1890, Jan. 2000.

[42] D. Verstraete, A. Gong, D. D.-C. Lu, and J. L. Palmer, "Experimental investigation of the role of the battery in the AeroStack hybrid, fuel-cell-based propulsion system for small unmanned aircraft systems," *Int. J. Hydrogen Energy*, vol. 40, no. 3, pp. 1598–1606, Jan. 2015.

[43] A. Nishizawa, J. Kallo, O. Garrot, and J. Weiss-Ungethüm, "Fuel cell and li-ion battery direct hybridization system for aircraft applications," *J. Power Sources*, vol. 222, pp. 294–300, Jan. 2013.

[44] J. Renau, F. Sánchez, A. Lozano, J. Barroso, and F. Barreras, "Analysis of the performance of a passive hybrid powerplant to power a lightweight unmanned aerial vehicle for a high altitude mission," *J. Power Sources*, vol. 356, pp. 124–132, Jul. 2017.

[45] W. Jiang and B. Fahimi, "Active current sharing and source management in fuel cell–battery hybrid power system," *IEEE Trans. Ind. Electron.*, vol. 57, no. 2, pp. 752–761, Feb. 2009.

[46] B. Wang *et al.*, "Current technologies and challenges of applying fuel cell hybrid propulsion systems in unmanned aerial vehicles," *Prog. Aerosp. Sci.*, vol. 116, Jul. 2020, Art. no. 100620.

[47] B. G. Gang and S. Kwon, "Design of an energy management technique for high endurance unmanned aerial vehicles powered by fuel and solar cell systems," *Int. J. Hydrogen Energy*, vol. 43, no. 20, pp. 9787–9796, May 2018.

[48] H. Rezk, A. M. Nassef, M. A. Abdelkareem, A. H. Alami, and A. Fathy, "Comparison among various energy management strategies for reducing hydrogen consumption in a hybrid fuel cell/supercapacitor/battery system," *Int. J. Hydrogen Energy*, vol. 46, no. 8, pp. 6110–6126, Jan. 2021.

[49] C. De Wagter *et al.*, "The NederDrone: A hybrid lift, hybrid energy hydrogen UAV," *Int. J. Hydrogen Energy*, vol. 46, no. 29, pp. 16003–16018, Apr. 2021.

[50] B. Lee, S. Kwon, P. Park, and K. Kim, "Active power management system for an unmanned aerial vehicle powered by solar cells, a fuel cell, and batteries," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 50, no. 4, pp. 3167–3177, Oct. 2014.

[51] Z. Yang, T. Lei, Z. Lin, H. Fu, and X. Zhang, "The testing platform of hybrid electric power system for a fuel cell unmanned aerial vehicle," in *Proc. IEEE Int. Conf. Electr. Syst. Aircr., Railway, Ship Propuls. Road Vehicles Int. Transp. Electrific. Conf. (ESARS-ITEC)*, Nov. 2018, pp. 1–8.

[52] T. Lei, Z. Min, H. Fu, W. Li, and X. Zhang, "Dynamic balanced energy management strategies for fuel cell hybrid power of unmanned air vehicle," (in Chinese), *Acta Aeronautica et Astronautica Sinica*, vol. 41, no. 12, Dec. 2020, Art. no. 324048.

[53] L. Karunarathne, J. T. Economou, and K. Knowles, "Power and energy management system for fuel cell unmanned aerial vehicle," *Proc. Inst. Mech. Eng., G, J. Aerosp. Eng.*, vol. 226, no. 4, pp. 437–454, Apr. 2012.

[54] X. Zhang, L. Liu, Y. Dai, and T. Lu, "Experimental investigation on the online fuzzy energy management of hybrid fuel cell/battery power system for UAVs," *Int. J. Hydrogen Energy*, vol. 43, no. 21, pp. 10094–10103, May 2018.

[55] B. Omar, A. Savvaris, R. O. Abdulhadi, M. K. Afdhol, and M. Hasibuan, "Saving hydrogen fuel consumption and operating at high efficiency of fuel cell in hybrid system to power UAV," *J. Earth Energy Eng.*, vol. 10, no. 1, pp. 32–42, Mar. 2021.

[56] Y. Shen, P. Cui, X. Wang, X. Han, and Y.-X. Wang, "Variable structure battery-based fuel cell hybrid power system and its incremental fuzzy logic energy management strategy," *Int. J. Hydrogen Energy*, vol. 45, no. 21, pp. 12130–12142, Apr. 2020.

[57] A. Ravey, B. Blunier, and A. Miraoui, "Control strategies for fuel-cell-based hybrid electric vehicles: From offline to online and experimental results," *IEEE Trans. Veh. Technol.*, vol. 61, no. 6, pp. 2452–2457, Jul. 2012.

[58] X. Zhang, L. Liu, and Y. Dai, "Fuzzy state machine energy management strategy for hybrid electric UAVs with PV/fuel cell/battery power system," *Int. J. Aerosp. Eng.*, vol. 2018, pp. 1–16, Jul. 2018.

[59] M. Gadalla and S. Zafar, "Analysis of a hydrogen fuel cell-PV power system for small UAV," *Int. J. Hydrogen Energy*, vol. 41, no. 15, pp. 6422–6432, Apr. 2016.

[60] E. Ozbek, G. Yalin, M. U. Karaoglan, S. Ekici, C. O. Colpan, and T. H. Karakoc, "Architecture design and performance analysis of a hybrid hydrogen fuel cell system for unmanned aerial vehicle," *Int. J. Hydrogen Energy*, vol. 46, no. 30, pp. 16453–16464, Apr. 2021.

[61] B. Vural *et al.*, "Fuel cell and ultra-capacitor hybridization: A prototype test bench based analysis of different energy management strategies for vehicular applications," *Int. J. Hydrogen Energy*, vol. 35, no. 20, pp. 11161–11171, Oct. 2010.

[62] S. Bayram and A. R. Boynuegri, "A comperative study on Wiener filter and wavelet transform for energy management systems on hybrid unmanned aerial vehicles," in *Proc. 6th Int. Conf. Electr. Power Energy Convers. Syst. (EPECS)*, Oct. 2020, pp. 112–117.

[63] M. N. Boukoberine, M. F. Zia, M. Benbouzid, Z. Zhou, and T. Donateo, "Hybrid fuel cell powered drones energy management strategy improvement and hydrogen saving using real flight test data," *Energy Convers. Manage.*, vol. 236, May 2021, Art. no. 113987.

[64] S. N. Motapon, L.-A. Dessaint, and K. Al-Haddad, "A comparative study of energy management schemes for a fuel-cell hybrid emergency power system of more-electric aircraft," *IEEE Trans. Ind. Electron.*, vol. 61, no. 3, pp. 1320–1334, Mar. 2014.

[65] T. Bradley, B. Moffitt, D. Parekh, T. Fuller, and D. Mavris, "Energy management for fuel cell powered hybrid-electric aircraft," in *Proc. 7th Int. Energy Convers. Eng. Conf.*, Aug. 2009, p. 4590.

[66] X. Li, Y. Wang, D. Yang, and Z. Chen, "Adaptive energy management strategy for fuel cell/battery hybrid vehicles using Pontryagin's minimal principle," *J. Power Sources*, vol. 440, Nov. 2019, Art. no. 227105.

[67] X. Sun, Y. Zhou, L. Huang, and J. Lian, "A real-time PMP energy management strategy for fuel cell hybrid buses based on driving segment feature recognition," *Int. J. Hydrogen Energy*, vol. 46, no. 80, pp. 39983–40000, 2021.

[68] X. Meng, Q. Li, W. Chen, and G. Zhang, "An energy management method based on pontryagin minimum principle satisfactory optimization for fuel cell hybrid systems," *Proc. CSEE*, vol. 39, no. 3, pp. 782–792, Feb. 2019.

[69] Z. Cheng, H. Liu, P. Yu, L. Zhu, and T. Sun, "Energy management for fuel cell/battery hybrid unmanned aerial vehicle," *Int. J. Electrochem. Sci.*, vol. 16, no. 10, pp. 1–17, Oct. 2021.

[70] Y. Xie, A. Savvaris, and A. Tsourdos, "Fuzzy logic based equivalent consumption optimization of a hybrid electric propulsion system for unmanned aerial vehicles," *Aerosp. Sci. Technol.*, vol. 85, pp. 13–23, Feb. 2019.

[71] H. Li, A. Ravey, A. N'Diaye, and A. Djerdir, "A novel equivalent consumption minimization strategy for hybrid electric vehicle powered by fuel cell, battery and supercapacitor," *J. Power Sources*, vol. 395, pp. 262–270, Aug. 2018.

[72] Y. Zhou, A. Ravey, and M.-C. Péra, "Multi-mode predictive energy management for fuel cell hybrid electric vehicles using Markov driving pattern recognizer," *Appl. Energy*, vol. 258, Jan. 2020, Art. no. 114057.

[73] C. Sun, X. Hu, S. J. Moura, and F. Sun, "Velocity predictors for predictive energy management in hybrid electric vehicles," *IEEE Trans. Control Syst. Technol.*, vol. 23, no. 3, pp. 1197–1204, May 2015.

[74] R. Zhang, J. Tao, and H. Zhou, "Fuzzy optimal energy management for fuel cell and supercapacitor systems using neural network based driving pattern recognition," *IEEE Trans. Fuzzy Syst.*, vol. 27, no. 1, pp. 45–57, Jan. 2019.

[75] D. Min, Z. Song, H. Chen, T. Wang, and T. Zhang, "Genetic algorithm optimized neural network based fuel cell hybrid electric vehicle energy management strategy under start-stop condition," *Appl. Energy*, vol. 306, Jan. 2022, Art. no. 118036.

[76] J. Yuan, L. Yang, and Q. Chen, "Intelligent energy management strategy based on hierarchical approximate global optimization for plug-in fuel cell hybrid electric vehicles," *Int. J. Hydrogen Energy*, vol. 43, no. 16, pp. 8063–8078, Apr. 2018.

[77] H. Sun, Z. Fu, F. Tao, L. Zhu, and P. Si, "Data-driven reinforcement-learning-based hierarchical energy management strategy for fuel cell/battery/ultracapacitor hybrid electric vehicles," *J. Power Sources*, vol. 455, Apr. 2020, Art. no. 227964.

[78] Y. Zhang, R. Ma, D. Zhao, Y. Huangfu, and W. Liu, "A novel energy management strategy based on dual reward function Q-learning for fuel cell hybrid electric vehicle," *IEEE Trans. Ind. Electron.*, vol. 69, no. 2, pp. 1537–1547, Feb. 2022.

[79] H. Shen, Y. Zhang, J. Mao, Z. Yan, and L. Wu, "Energy management of hybrid UAV based on reinforcement learning," *Electronics*, vol. 10, no. 16, p. 1929, Aug. 2021.

[80] M. A. Latif, "An agricultural perspective on flying sensors: State of the art, challenges, and future directions," *IEEE Geosci. Remote Sens. Mag.*, vol. 6, no. 4, pp. 10–22, Jul. 2018.

[81] G. Potrino, N. Palmieri, V. Antonello, and A. Serianni, "Drones support in precision agriculture for fighting against parasites," in *Proc. 26th Telecommun. Forum (TELFOR)*, Nov. 2018, pp. 1–4.

[82] R. Ke, Z. Li, S. Kim, J. Ash, Z. Cui, and Y. Wang, "Real-time bidirectional traffic flow parameter estimation from aerial videos," *IEEE Trans. Intell. Transp. Syst.*, vol. 18, no. 4, pp. 890–901, Apr. 2016.

[83] *Commercial UAV Expo Americas Virtual Event, To Be Held September 15–17*. Accessed: Aug. 19, 2020. [Online]. Available: https://insidetowers.com/cell-tower-news-att-working-make-drone-tower-inspections-intelligent/

[84] F. Mohamadi, "Vertical takeoff and landing (VTOL) small unmanned aerial system for monitoring oil and gas pipelines," U.S. Patent 8 880 241, Nov. 4, 2014.

[85] K. P. Valavanis and G. J. Vachtsevanos, *Handbook of Unmanned Aerial Vehicles*. Berlin, Germany: Springer, 2015.

[86] F. P. G. Márquez and I. S. Ramírez, "Condition monitoring system for solar power plants with radiometric and thermographic sensors embedded in unmanned aerial vehicles," *Measurement*, vol. 139, pp. 152–162, Jun. 2019.

[87] L. Wang and Z. Zhang, "Automatic detection of wind turbine blade surface cracks based on UAV-taken images," *IEEE Ind. Electron. Mag.*, vol. 64, no. 9, pp. 7293–7303, Sep. 2017.

[88] Z. Zhou, C. Zhang, C. Xu, F. Xiong, Y. Zhang, and T. Umer, "Energy-efficient industrial internet of UAVs for power line inspection in smart grid," *IEEE Trans. Ind. Informat.*, vol. 14, no. 6, pp. 2705–2714, Jun. 2018.

[89] H. Abaunza and P. C. Garcia, "Les applications de drones aériens-L'utilisation civile desUAVs," (in French), Techn. de l'Ingenieur, Aug. 2017.

[90] T. F. Villa, F. Gonzalez, B. Miljievic, Z. D. Ristovski, and L. Morawska, "An overview of small unmanned aerial vehicles for air quality measurements: Present applications and future prospectives," *Sensors*, vol. 16, no. 7, p. 1072, 2016.

[91] W. Zang, J. Lin, Y. Wang, and H. Tao, "Investigating small-scale water pollution with UAV remote sensing technology," in *Proc. World Automat. Congr.*, 2012, pp. 1–4.

[92] T. H. Bradley, B. A. Moffitt, T. F. Fuller, D. N. Mavris, and D. E. Parekh, "Comparison of design methods for fuel-cell-powered unmanned aerial vehicles," *J. Aircr.*, vol. 46, no. 6, pp. 1945–1956, Nov. 2009.

[93] L. Kohout and P. Schmitz, "Fuel cell propulsion systems for an all-electric personal air vehicle," in *Proc. AIAA Int. Air Space Symp. Expo., Next 100 Years*, Jul. 2003, p. 2867.

[94] A. Himansu, J. E. Freeh, C. J. Steffen, R. T. Tornabene, and X.-Y. J. Wang, "Hybrid solid oxide fuel cell/gas turbine system design for high altitude long endurance aerospace missions," Tech. Rep. NASA/TM-2006-214328, 2006.

[95] B. A. Moffitt, T. H. Bradley, D. E. Parekh, and D. N. Mavris, "Design space exploration of small-scale PEM fuel cell unmanned aerial vehicle," in *Proc. AIAA*, Sep. 2006, Paper 7701.

[96] N. Lapeña-Rey, J. A. Blanco, E. Ferreyra, J. L. Lemus, S. Pereira, and E. Serrot, "A fuel cell powered unmanned aerial vehicle for low altitude surveillance missions," *Int. J. Hydrogen Energy*, vol. 42, no. 10, pp. 6926–6940, Mar. 2017.

[97] T. H. Oh, "Conceptual design of small unmanned aerial vehicle with proton exchange membrane fuel cell system for long endurance mission," *Energy Convers. Manage.*, vol. 176, pp. 349–356, Nov. 2018.

[98] B. Wang *et al.*, "Current technologies and challenges of applying fuel cell hybrid propulsion systems in unmanned aerial vehicles," *Prog. Aerosp. Sci.*, vol. 116, Jul. 2020, Art. no. 100620.

[99] F. G. Harmon, "Neural network control of a parallel hybrid-electric propulsion system for a small unmanned aerial vehicle," Ph.D. dissertation, Dept. Mech. Aeronaut. Eng., Univ. California-Davis, Davis, CA, USA, 2005.

[100] Q. Li, X. Meng, F. Gao, G. Zhang, and W. Chen, "Approximate cost-optimal energy management of hydrogen electric multiple unit trains using double Q-learning algorithm," *IEEE Trans. Ind. Electron.*, vol. 69, no. 9, pp. 9099–9110, Sep. 2022.

[101] Z. Yu, D. Zinger, and A. Bose, "An innovative optimal power allocation strategy for fuel cell, battery and supercapacitor hybrid electric vehicle," *J. Power Sources*, vol. 196, no. 4, pp. 2351–2359, 2011.

[102] J. Zhao, X. Li, C. Shum, and J. McPhee, "A review of physics-based and data-driven models for real-time control of polymer electrolyte membrane fuel cells," *Energy AI*, vol. 6, Dec. 2021, Art. no. 100114.

[103] D. Oryshchyn, N. F. Harun, D. Tucker, K. M. Bryden, and L. Shadle, "Fuel utilization effects on system efficiency in solid oxide fuel cell gas turbine hybrid systems," *Appl. Energy*, vol. 228, pp. 1953–1965, Oct. 2018.

[104] Q. Li, X. Meng, F. Gao, G. Zhang, W. Chen, and K. Rajashekara, "Reinforcement learning energy management for fuel cell hybrid system: A review," *IEEE Ind. Electron. Mag.*, early access, Feb. 21, 2022, doi: 10.1109/MIE.2022.3148568.

[105] Z. Hua, Z. Zheng, E. Pahon, M.-C. Péra, and F. Gao, "A review on lifetime prediction of proton exchange membrane fuel cells system," *J. Power Sources*, vol. 529, May 2022, Art. no. 231256.

[106] Z. Gong *et al.*, "A 1 + 1-D multiphase proton exchange membrane fuel cell model for real-time simulation," *IEEE Trans. Transport. Electrific.*, vol. 8, no. 2, pp. 2928–2944, Jun. 2022.

[107] Z. Hua, Z. Zheng, M.-C. Péra, and F. Gao, "Statistical analysis on random matrices of echo state network in PEMFC system's lifetime prediction," *Appl. Sci.*, vol. 12, no. 7, p. 3421, Mar. 2022.

Liangcai Xu (Member, IEEE) received the B.Eng. degree in measurement and control technology and instrument and the master's degree in electrical engineering from Northwestern Polytechnical University, Xi'an, China, in 2018 and 2021, respectively. He is currently pursuing the Ph.D. degree with the Department of Mechanical Engineering, National University of Singapore, Singapore.

After graduation, he worked as a Research Assistant at Northwestern Polytechnical University from 2021 to 2022. His research interests include advanced and fault-tolerant control for power electronics, and optimization of storage system and its application in power systems.

Yigeng Huangfu (Senior Member, IEEE) received the M.S. and Ph.D. degrees in electrical engineering from Northwestern Polytechnical University (NPU), Xi'an, China, in 2007 and 2009, respectively, and the Ph.D. degree from the University of Technology of Belfort-Montbéliard, Belfort, France, in 2010.

He has been a Full Professor with NPU. His main research interests include power electrical conversion, transportation electrification, intelligence control of new energy conversion, and renewable energy generation technology.

Dr. Huangfu is currently the Chair of the IEEE IES Technical Committee on Transportation Electrification. He is also an Associate Editor of IEEE Industrial Electronics and Application and *IET Power Electronics*.

Rui Ma (Senior Member, IEEE) received the master's degree in electrical engineering from Northwestern Polytechnical University (NPU), Xi'an, China, in 2016, and the dual Ph.D. degree in electrical engineering from the University of Technology of Belfort-Montbéliard (UTBM), Belfort, France, and NPU, in 2018 and 2019, respectively.

He is currently an Associate Professor with the School of Automation, NPU. His main research interests include fuel cell modeling, fuel cell applications, real-time simulation systems, and machine learning.

Dr. Ma served as a member of the Technical Committee on Transportation Electrification for the IEEE Industrial Electronics Society and the Special Session Chair for 45th, 46th, and 47th IEEE IECON. He serves as an Associate Editor for IEEE IES Industrial Electronics Technology News and a Distinguish Reviewer for IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS.

Renyou Xie (Member, IEEE) received the bachelor's degree in electrical engineering from the School of Automation, Northwestern Polytechnical University (NPU), Xi'an, China, in 2018, and the master's degree in electrical engineering from NPU in 2021.

He is currently a Research Assistant with Central South University, Changsha, China. His current research interests include fuel cells, federated learning, and renewable energy systems.

Ziyou Song (Member, IEEE) received the B.E. and Ph.D. degrees (Hons.) in automotive engineering from Tsinghua University, Beijing, China, in 2011 and 2016, respectively.

After graduation, he worked as a Research Scientist at Tsinghua University from 2016 to 2017. From 2017 to 2019, he worked as a Post-Doctoral Research Fellow at the University of Michigan, Ann Arbor, MI, USA, where he was an Assistant Research Scientist/Lecturer from 2019 to 2020. He is currently an Assistant Professor with the Department of Mechanical Engineering, National University of Singapore, Singapore. Prior to joining NUS, he was a Battery Algorithm Engineer at Apple Inc., Cupertino, CA, USA, where he was in charge of battery management system for audio products (e.g., AirPods). He is the author or the coauthor of two book chapters and more than 60 peer-reviewed publications, including 40 journal articles. His research interests lie in the areas of modeling, estimation, optimization, and control of energy storage (e.g., battery, supercapacitor, and flywheel) for electrified vehicles and renewable energy systems. Using energy storage as a bridge, his group is actively connecting the automotive, transportation, and power system communities by collaborating on interdisciplinary projects to ensure that both power system and transportation system are efficient, reliable, and clean.

Dr. Song received several paper awards, including the Applied Energy 2015–2016 Highly Cited Paper Award, the Applied Energy Award for Most Cited Energy Article from China, the NSK Outstanding Paper Award of Mechanical Engineering, and the 2013 IEEE VPPC Best Student Paper Award. He serves as a reviewer for more than 40 international journals. He also serves as an Associate Editor for *Automotive Innovation*, *SAE International Journal of Electrified Vehicles*, and IEEE TRANSACTIONS ON TRANSPORTATION ELECTRIFICATION.

Dongdong Zhao (Member, IEEE) received the B.Eng. degree in information antagonizing technology from Northwestern Polytechnical University, Xi'an, China, in 2008, and the Ph.D. degree in electrical engineering from the University of Technology of Belfort-Montbéliard, Belfort, France, in 2014.

Since 2014, he has been an Associate Professor with Northwestern Polytechnical University. His research interests include fuel cell system modeling and control, power electronics, and motor drives.

Yongheng Yang (Senior Member, IEEE) received the B.Eng. degree in electrical engineering and automation from Northwestern Polytechnical University, Xi'an, China, in 2009, the master's degree from Southeast University, Nanjing, China, in 2011, and the Ph.D. degree in energy technology (power electronics and drives) from Aalborg University, Aalborg, Denmark, in 2014.

In 2013, he was a Visiting Scholar at Texas A&M University, College Station, TX, USA. From 2014 to 2020, he was with the Department of Energy Technology, Aalborg University, where he became a tenured Associate Professor in 2018. In January 2021, he joined Zhejiang University, Hangzhou, China, as a ZJU100 Professor. His research focuses on the grid integration of photovoltaic systems and control of power converters, in particular, the grid-forming technologies.

Dr. Yang is currently the Secretary of the IEEE PELS Technical Committee on Sustainable Energy Systems and a Council Member of the China Power Supply Society. He was the Chair of the IEEE Denmark Section from 2019 to 2020. He is an associate editor for several IEEE TRANSACTIONS. He was a recipient of the 2018 IET Renewable Power Generation Premium Award, the 2021 Richard M. Bass Outstanding Young Power Electronics Engineer Award from the IEEE Power Electronics Society (PELS), and the 2022 Isao Takahashi Power Electronics Award. He was an Outstanding Reviewer of the IEEE TRANSACTIONS ON POWER ELECTRONICS in 2018. He received two IEEE best paper awards. He has been included on the list of Highly Cited Chinese Researchers by Elsevier in 2022.

Yupeng Wang (Senior Member, IEEE) received the M.E. degree in electrical engineering from the University of Technology of Belfort-Montbéliard (UTBM), Belfort, France, in 2013.

He is currently the Team Leader of the fuel cell system performance with FAW, Changchun, China. He is mainly responsible for the performance design, strategy development, virtual simulation, and data analysis of the fuel cell system.

Liangfei Xu received the B.E. and Ph.D. degrees from Tsinghua University, Beijing, China, in 2003 and 2009, respectively.

From November 2015 to August 2017, he was with Forschungszentrum Jülich, Jülich, Germany, as an Alexander von Humboldt Research Fellow. In October 2017, he was promoted to an Associate Professor at the School of Vehicle and Mobility, Tsinghua University. He is currently an Associate Professor and the Deputy Director of the School of Vehicle and Mobility, Vehicular Powertrain Engineering Institute, Tsinghua University. His research interests include the design, diagnosis, control, and health management of polymer electrolyte membrane (PEM) fuel cells and powertrains for electric vehicles.

Dr. Xu serves as an Associate Editor for *International Journal of Powertrains* and an Editorial Board Member for *eTransportation*. He received the 5th ProSPER.NET-Scopus Young Scientist Award in 2013, the First Prize of China Automotive Industry Science and Technology Award in 2019, the Science Fund Program for Distinguished Young Scholars in 2020, the First Prize of Beijing Science and Technology Award in 2021, and the Outstanding Young Technological Talent Award of China Automobile Industry in 2021.